THE INTERCEPTION OF RAINFALL BY FOREST CANOPIES IN SOUTH EAST SCOTLAND

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SUMMARY

This thesis reports on a study of the interception of precipitation by forest canopies. The experiment was carried out at Dalmeny Estate near Edinburgh in South-East Scotland. Gross precipitation, throughfall and stemflow were measured on a weekly basis and interception was determined for stands of Scots Pine (*Pinus sylvestris*), Beech (*Fagus sylvatica*) and Sycamore (*Acer pseudoplatanus*). The experiment spanned an 18-month period from 6 May 1977 to 2 November 1978.

The results obtained indicate that, on average, Pine intercepted 34% to 47% of the gross precipitation against 30% for Beech and 12% to 21% for Sycamore. Stemflow was found to be negligible on Pine, amounting to 1% to 2% of the gross precipitation, whereas it accounted for 17% and 9% of the precipitation falling on Beech and Sycamore respectively.

The role of the interception is duscussed and it is shown that interception loss has an important place in the water-balance equation of the stands studied. It is argued, however, that the total annual water consumption of these stands might not exceed the estimated potential evapotranspiration in this area. This is because South-East Scotland is relatively dry and, as a result of this, interception loss does not amount to as much as in very wet areas elsewhere in Britain.

The conclusion is that Sycamore intercepts much less precipitation than Pine or Beech, therefore it might be a better choice in plantations in catchment areas where there is a great demand for water.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

APPENDIX

PART I

I.1 INTRODUCTION

Interception of precipitation by forest canopies is one of the most intensively studied phases of the forest water balance. This is probably due to its significant hydrological role and also to the fact that it can easily be measured.

According to Molchanov (1960), the first investigations were conducted in 1863 by Krutzsch in a Pine forest in West Germany. Since then, many experiments have been carried out in various parts of the world. As a result, a great deal is now known about the magnitude of interception loss in different types of forest and climate. This work has been extensively reviewed by Kittredge (1948), Molchanov (1960), Penman (1963), Zinke (1967), Delfs (1967), Rutter (1975), Ward (1975) and Miller (1977). The following summary and discussion is based mainly on these reviews as well as some of the important individual papers.

It is generally accepted that interception is best defined as the process by which rainfall is caught by the vegetation canopy and redistributed as throughfall, stemflow, absorption and evaporation from the vegetation. To quote Horton (1919):

"When rain begins, drops striking leaves are mostly retained, spreading over the leaf surfaces in a thin layer or collecting in drops or blotches at points, edges, or on ridges or in depressions of the leaf surface. Only a meager spattered fall reaches the ground, until the leaf surfaces have retained a certain volume of water, dependent on the position of the leaf surface, whether horizontal or inclined, on the form of the leaf, and on the surface tension relations between the water and the leaf surface, on the wind velocity, the intensity of the rainfall, and the size and impact of the falling drops. When the maximum surface storage capacity for a given leaf is reached, added water striking the leaf causes one after another of the drops to accumulate on the leaf edges at the lower points. Each drop grows in size (the air being still) until the weight of the drop overbalances the surface tension between the drop and the leaf film, when it falls, perhaps to the ground, perhaps to a lower leaf hitherto more sheltered. These drops may also be shaken off by wind or by impact of rain on the leaf. The leaf system temporarily stores the precipitation, transforming the original rain drops usually into larger drops. In the meantime the films and drops on the leaves are freely exposed to evaporation".

The forest canopy dries up by evaporation after the rainfall has ceased and remains dry until the next rain event when the process repeats itself again.

The amount of interception loss depends on numerous factors. Some are related to the physical features of the forest itself, while others are the meteorological factors that determine the evaporative demands of the atmosphere in a given period of time. The amount and the pattern of distribution of precipitation in time are also significant factors. For this reason, the results of interception values reported in the literature show considerable variation.

In general, for example, interception in a coniferous forest is much greater than a deciduous forest even during the summer season. It ranges approximately from 15% to 40% of annual precipitation in conifers, and from 10% to 25% in deciduous forests (Rutter, 1975).

Variations between summer and winter due to the deciduous habit have also been reported by many investigators so that a greater portion of precipitation is lost as interception during summer when the trees are in leaf. However, the amount of decrease in winter interception is variable (Kittredge 1948, Helvey and Patric 1965 a). It is interesting to note that forest canopies without leaves do intercept precipitation, perhaps more than expected.

Interception amount also varies with the stand density, canopy closure and silvicultural treatments such as thinning. For a given type of forest, the proportion of interception increases with increasing canopy and stand density. However, Kittredge (1948) pointed out that this relationship was not linear. Wilm (1943) measured interception in Lodgepole Pine (Pinus contorta var. latifolia Engelm) in Colarado U.S.A. on small plots where various degrees of thinning had been implemented. The results showed that interception decreased with an increasing degree of thinning ranging from 31% of the annual precipitation in unthinned stands to 7% in those where all trees of more than 24 cm. diameter had been removed.

It is important to note that the absolute interception value also depends on the rain climate of a given area. Greater losses have been reported for high rainfall regions than for relatively dry ones. The results obtained by the Institute of Hydrology in the United Kingdom at Thetford and Hafren forests illustrate this point. The loss at the dry site (Thetford) was 214mm. compared to 790mm. at the very wet Hafren site (Gash and Stewart 1977, Calder 1976).

It has also been shown that, in areas of similar annual precipitation, variations in the frequency of rain events can produce marked differences in interception loss (Leonard 1967, Rutter 1975). This is because the interception is partly dependent on the frequency of the wetting of the forest canopy (Leonard 1967, Rutter 1975).

In the preceding discussion, interception loss has been considered as that part of precipitation that is retained by and evaporated from the forest canopy without reaching the forest floor. This by no means reveals the quantitative significance of interception in the overall water balance of a forest. However, the opinions on this matter vary. Early workers believed that the interception value estimated as the precipitation landing on the canopy minus precipitation measured beneath should be regarded as an extra water loss in the water balance equation. Horton (1919), for example, said that it represented a loss which would otherwise be available to the soil. Arguing on similar lines, Hirata (1929), cited by Leyton et al (1967), said:

"The amount of the increase in runoff (after clearing the forest) is one of the same order as that portion of the rainfall which would be expected to be intercepted by the tree crowns had they not been felled".

This opinion was later challenged by Penman during the late

1940's and 50's who argued that most of the intercepted water was re-evaporated and became part of the evaporation term in the hydrological balance sheet (Penman, 1963). He based his argument on the fact that the same energy cannot be used twice. If energy is being used to evaporate intercepted water, it cannot also be evaporating transpired water.

Burgy and Pomeroy (1958) showed that interception loss in small grass plots grown in nutrient solution was completely compensated by a reduction in transpiration. Although moisture was retained and did evaporate, the artificially wetted grass leaves caused no excess water loss. This finding was substantiated by the results reported by McMillan and Burgy (1960) who worked the grasses grown in weighing lysimeters in field conditions.

The results of Law's (1958) experiments on the other hand showed that the results obtained from experiments with grass could not be extended to forests. His interception estimate was so high that it even exceeded the evaporation from an open water surface during winter as estimated according to the Penman Formula (E_o). Unfortunately, Law's result was unjustifiably criticised on the basis that his small plantation was too exposed to be representative of a continuous forest. Nevertheless, the results of more recent work by Rutter (1963, 1967) in Bramshill Forest (Scots Pine - Pinus sylvestris L.) in Berkshire, England and those of the Thetford and Hafren experiments have clearly revealed that conifer forests are characterized by high interception loss.

High interception loss is attributed to the evaporation of the intercepted water which generally occurs at rates several times greater than transpiration under the same meteorological conditions. This is because the rate of transpiration is controlled by stomatal resistance of the leaves, whereas a wet canopy surface exerts negligible resistance to vapour flux. The evaporation rate of intercepted water can often exceed even the net available net radiation energy expressed as a water depth equivalent, the deficit being supplied by the cooling of the air within the canopy and the advection of heat from other areas in the vicinity of the forest. However, no quantitative information is available as to how much energy is supplied in this way (Rutter 1963 and 1967, Stewart and Thom 1973, Murphy and Knoer 1975, Stewart 1977, Gash and Morton 1978, McNaughton and Black 1973, Singh and Szeicz 1979). Transpiration from grass is not limited in the same way and, therefore, evaporation of both intercepted and transpired water occurs at similar rates, thus causing no extra water loss. This feature leads to the conclusion that interception of precipitation by forests represents a loss of water to the soil although the amount of net loss is not equal to the interception loss estimated as the difference between precipitation landing on the canopy and that of measured beneath it, because transpiration is suppressed while the canopy remains wet. The implication is, therefore, that interception as an important component in the water balance of a forest should be taken into account in forestry practice and watershed management.

Although in most situations, the interception of precipitation by trees reduces the amount of water reaching the soil, there are situations where the reverse may happen.

One such situation is where trees are in direct contact with condensation v. interception

dense fog for considerable periods of time, resulting in what is called "fog drip". Fog is mostly formed over the sea and blown by wind towards the coasts. Condensation takes place when the air borne water particles are in direct contact with cool surfaces of various types. However, it has been shown that vegetation is much better suited than bare soil and rocks, owing to the greater surface area and to the increased turbulent eddies (Nagel, 1956). Trees are particularly effective in this respect. Oura (1953), for example, reported that the amount of fog drip under deciduous trees on the Hokkaido Island (Japan) was 6 to 10 times as much as that caught by the open field.

Azevedo and Morgan (1974) measured that net water condensated on a Douglas Fir in the coastal California forests amounted to as much as 880mm. during a 46-day summer period on 28 foggy days. Ekern (1964) measured fog drip under a Monkey Puzzle, Araucaria excelsa (Molina) C. Koch., on the Lanaii Island (Hawaii) to be 762mm. per annum. It is interesting to note that these amounts were measured under trees at times when no rainfall was recorded in neighbouring open fields. It has also been shown that fog drip increased with the height of vegetation and with the increasing wind speed (Kittredge 1948, Yosida and Kuroiva 1953, Costin and Wimbush 1961). The amount of water condensated by forest trees can be so great that interception loss by the same trees may be totally compensated or, at least, greatly reduced (Hirata 1929, Grunov 1955; both cited in Penman 1963).

Nevertheless, it is apparent from the geographical distribution of fog precipitation that it is mainly a feature of climate and is restricted to certain localities on the earth where prolonged dense fogs are prevalent (Penman 1963, Lamb1965, Rutter 1975). It has also been shown that a considerable amount of fog drip occurs at forest margins where trees are fully exposed to fog carrying winds, whereas this effect drastically diminishes in the interior of forests. This suggests that fog drip is principally an edge effect not reaching far into a forest. Its significance, therefore, should not be overestimated (Kittredge 1948, Oberlander 1956, Penman 1963, Azevedo and Morgan 1974).

Apart from inducing fog condensation, it has also been argued by some, notably foresters, that forests exert some control over the amount of precipitation actually falling on them. Zon (1927), cited in Kittredge (1948), for example, claimed that forests increased both the abundance and frequency of local precipitation over the areas they occupied by up to 25%. Such an effect has been generally attributed to increased friction exerted by rough forest surfaces and to increased effective height of the ground. Hursh and Connaughton (1938) measured precipitation both in a large area in the Copper Basin (U.S.A.), which was denuded by smelter fumes, and in small clearings in the surrounding original hardwood forest. Records obtained for a two year period showed that the forest clearings received from 17.5% to 28% more precipitation than the open denuded site. Although numerous measurements and comparisons of this kind have also been made elsewhere, notably in the continental European countries, it has been difficult to show whether any such differences detected could be attributed to positive forest influence in increasing precipitation. In his review paper, Brooks (1928), for example, accepted a difference of up to 10% between forest and open field, but he concluded that only 1% could be due to the net effect of forest, the remaining being owing to the sheltering effect of trees on raingauges used in forest clearings. An increase of 1% is what could be expected from the increase of the effective height of the ground brought about by the presence of a forest (Brooks 1928, Kittredge 1948).

Many meteorologists, however, do not accept that forest has any effect in increasing precipitation (Geiger, 1965). They argued that the formation of precipitation takes place in the upper atmosphere and is not affected by vegetation cover.

The overall conclusion that is generally accepted from the conflicting opinions presented above is that although vegetation may affect the disposal of precipitation, it cannot affect the amount of precipitation to be disposed (Geiger 1960, Penman 1963).

It is clear from the previous account that a great deal is known about the process and the magnitude of interception by forest canopies. However, it is equally clear that much still remains to be discovered. This is particularly the case in Britain where it has recently been shown that interception is far more important than was formerly believed. The implication of data from the Hafren experiments cited earlier is that afforestation of rough grazing land in the British uplands could reduce considerably the water yield of catchment areas. Such reduction is accounted for by the fast evaporation of intercepted water. The extent to which these results can be extrapolated to other areas is, however, a matter for debate (Jarvis 1979). Therefore, it is clear that there is a need for data to be collected in other areas of the country where no information is available on the interception by forest trees. It is also of considerable importance to know whether interception values vary amongst the main forest tree species, both deciduous and conifer (evergreen). Ovington (1954) measured interception in 13 different species in a small locality at Bedgebury, Kent. However, his analyses are not exhaustive enough to reveal whether the species differences could be accepted as significant. For this reason, there is also need for research in order to detect any species variation in interception.

The present work reports on a study of various aspects of interception of precipitation by different forest canopies at Dalmeny Estate near Edinburgh in south-east Scotland. It falls into 5 parts: Part I comprises this Introduction and a review of the literature of methodology used so far in interception studies. Part II consists of a detailed description of the location and its climate, where the present experiments were conducted. In Part III, the methodology and instrumentation used in the experiments are discussed. Part III is divided up into 3 sections: the first section deals with methods of measuring gross precipitation, and subsequent sections are concerned with the problems of measuring throughfall and stemflow respectively. The results obtained from the experimental data are presented in Part IV under 2 sections: one deals with the results of interception by a pine forest, the other with deciduous tree species. Finally, in Part V, the results and findings are discussed and consequent conclusions are made.

I.2 REVIEW OF METHODS USED IN PREVIOUS INTERCEPTION EXPERIMENTS

The purpose of this part of the thesis is to review the various methods used to date in interception studies. A critical approach is adopted to reveal the advantages and disadvantages of the methods described.

For convenience, the methods may be divided into two major groups:

i) The traditional method.

ii) Other methods.

I.2.1 The Traditional Method

This method is based on the principle that the interception loss is the difference between the amount of gross precipitation and net precipitation as measured in open ground or above forest canopy and forest, respectively. This can be expressed by the equation:

$$I = G - N \qquad \text{Formula (1)}$$

where I is interception, G is gross precipitation that is the amount of precipitation landing on the forest canopy, N is net precipitation defined as the quantity of rainfall which actually reaches the ground; all elements being expressed in water depth units, generally milimetres. The net precipitation is the sum of throughfall and stemflow:

$$N = T + S \qquad \text{Formula (2)}$$

where T is throughfall defined as the portion of the rainfall which reaches the ground directly through the vegetative canopy and through openings and as drip from leaves, twigs and stems. S is stemflow which is the portion of the rainfall that, having been intercepted by the canopy, reaches the ground by running down the stems. Combining equations 1 and 2, the relationship becomes:

$$I = G - (T + S) \qquad \text{Formula (3)}$$

It is apparent from equation 3 that interception is estimated indirectly by a subtraction. Direct measurements of interception are extremely difficult and, as can be seen in the following sections, a direct method of interception is not readily available.

The traditional method requires the measurements of the three unknowns G, T and S in order to give an estimate of interception I. Each of these variables has to be sampled by special instrumentation and procedure. For this reason, it is appropriate here to deal with them separately.

I.2.1.1 Gross Precipitation

Gross precipitation is the amount of precipitation that actually falls on the forest canopy. The measurement of this component is of primary importance for it dictates the accuracy of the estimate of interception.

I.2.1.1.1 Instrumentation

Gross precipitation is measured by means of raingauges which vary in type. Two main types are the recording gauge and the non-recording raingauge. The construction of recording gauges is based on such systems as weighing, floating and tipping-bucket (Toebes and Ouryvaev, 1970). These gauges are generally more sophisticated and more expensive than the non-recording ones. However, they provide detailed information on rainfall amount, its duration and intensity. Furthermore, such information is obtained while the gauge is installed unattended.

A non-recording raingauge, on the other hand, has a much simplier construction. It consists of a receiver, often circular, with its rim area known very accurately, perhaps to the nearest 0.5% (W.M.O., 1974) and a collector in which rain water is stored. The gauge simply collects the rain, but does not record. Therefore, the measurement is made manually on a daily, weekly or monthly basis; the interval depending on the purpose of the measurement.

The accurate measurement of gross precipitation is known to be a difficult task because of the various errors involved. Wetting of the raingauge surface, for example, is reported to amount to about 0.2mm. per measurement. Evaporation from the gauges is also a source of error amounting up to 6% of summer precipitation (Toebes and Ouryvaev,1970); although measures can be taken to reduce this by constructing a narrow neck in the receiver or by adding oil to the rain water (W.M.O., 1974). During winter, there can be water leakage from the collector due to frost damage. To combat this, anti-freeze can be added. Another example of instrumental errors is wrong calibration of the measuring tube. One of the most common errors is human error, a particularly common one being spillage of water while making readings.

By far the most important errors, however, are those resulting from inherent deficiencies in the design and location of the raingauge itself. Rainfall measurement in any given location is generally based on the assumption that a raingauge measures the quantity of water reaching the earth's surface. However, Rodda (1967) pointed out that this assumption is not valid because of the effect of wind which plays a significant role in reducing the rain-catch of the gauge. A raingauge acts as an obstacle to the airflow and, thus, causes turbulence and eddying just over its rim. Some rain drops are then blown away off the orifice of the gauge. The effect is to underestimate the amount of precipitation actually falling on the ground surface.

Devices such as turf walls and wind shields of various types have frequently been used to reduce this wind effect. These devices aim to modify the surroundings of a gauge, so that a parallel airflow pattern occurs over the rim. However, the most effective way of avoiding wind effect is perhaps to install the raingauge at ground level in a special anti-splash device such as a metal slat grid. Such a raingauge is generally call a "ground level raingauge". Rodda (1967), for example, reported that his 127mm. standard raingauge (British Met. Office Mk.2) 30.5cm. above the ground measured 6.6%

less than a ground level raingauge installed in the vicinity. Green (1970) also detected differences of a similar magnitude between various gauge types as well as between gauges installed at different heights. However, neither Rodda (1967) nor Green (1970) found persistent and straightforward relationships between gauge catch and wind speed or the height of the rim above the ground.

In interception experiments, gross precipitation has to be measured either just above the forest canopy level or in forest clearings. If precipitation is to be measured above the canopy, wind shields must be fitted to the gauges (Ward, 1975). Davis (1939) described a simple wooden construction to hoist gauges at canopy level. However, measurement of gross precipitation at this level is not an easy task. Law (1957) and Reynolds and Leyton (1963), for example, reported that gauge catch differed with the height of the gauge above the canopy and with the type of shield used. Therefore, measurements in forest openings are often preferred to those at canopy level. Reviewing the studies of interception in Eastern Hardwoods of the U.S.A., Helvey and Patric (1965 a) reached the conclusion that rainfall measurements in forest openings are as accurate as those at canopy level. They also suggested that such openings should be situated on similar slopes and aspects as those used for sampling throughfall. In any case, a gross precipitation gauge should be placed at a sufficient distance from surrounding trees, so that the angle between the ground surface and the line drawn from the orifice of the gauge to the top of any neighbouring tree is not more than 45°. This ensures that trees do not interfere with the gauge catch (Helvey and Patric, 1965 a).

I.2.1.1.2 Number of Raingauges used in the Sampling of Gross Precipitation

In an interception experiment, it is desirable to measure accurately the gross precipitation falling on the forest canopy within the experimental plot in a given period of time. Apart from the difficulties mentioned earlier regarding the point measurements, this involves the consideration of the variation of precipitation in space, i.e. spatial variation. It is only natural that if the study area is small and large differences in elevation do not occur, then only one raingauge can be considered sufficient in accordance with the assumption that rainfall is most likely to be distributed fairly evenly over the plot concerned. On the other hand, large areas with topographical variations will require particular attention to the sampling of rainfall in order to achieve accurate measurements. This has been well appreciated by investigators, and various numbers of gauges have been used (a list of which is provided in Table 1). These numbers vary from 1 to 16, but are mostly under 5.

In most experiments, however, the number of gauges used has been chosen arbitrarily; an approach which does not appear to be fully satisfactory. This matter has been carefully studied by Helvey and Patric (1965 b) who, in an attempt to solve the problem, recommended the use of the following formula of statistical origin:

$$n = \frac{t^2 s^2}{d^2} \qquad \text{Formula (4)}$$

where n is the number of gauges, t is a tabulated value obtainable

Table 1 Number of Raingauges Used by Various Investigators to Measure Gross Precipitation.

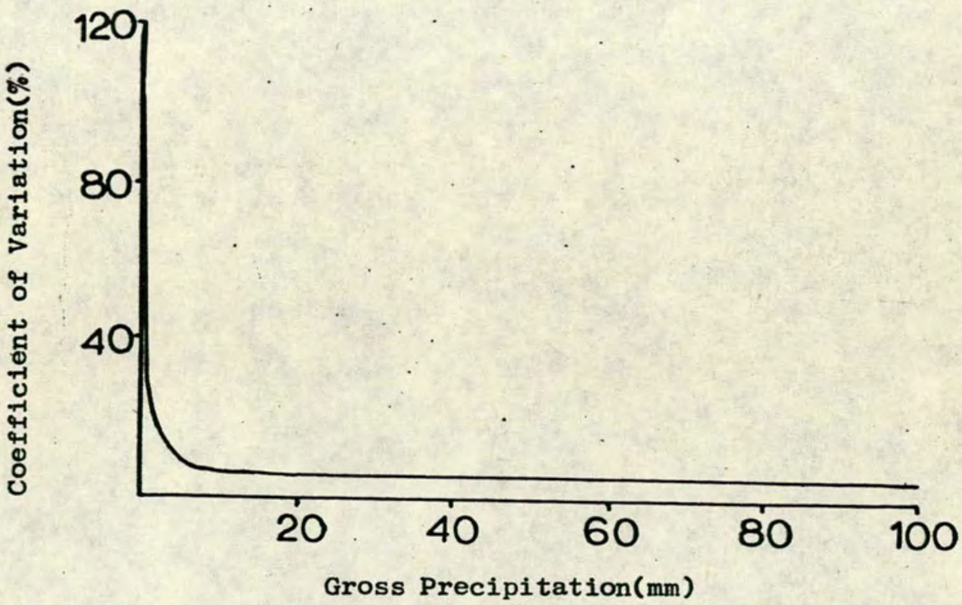
Reference	Country	Num. of Gauges
Rothacher(1963)	Oregon, USA	1
Wilm(1943)	Colorado, USA	1
Trimble & Weitzman(1954)	W.Virginia, USA	1
Rutter(1963)	Berks, UK	2
Thorud(1963)	Minnesota, USA	2
Singh & Szeicz(1979)	Canada	2
Rogerson(1965)	Mississippi, USA	3
Law(1957)	Yorkshire, UK	3
Carlisle et al(1965)	Lancashire, UK	3
Horton(1919)	New York, USA	3
Orr(1972)	S.Dakota, USA	3
Jackson(1971 a and b)	Tanzania	4
Ford & Deans(1978)	Scotland, UK	5
Rowe & Hendrix(1951)	California, USA	8
Ovington(1954)	Kent, UK	10
Slatyer(1965)	N.Territory, AUSTR.	12
Reynolds & Leyton(1963)	Oxford, UK	16
Gash & Stewart(1977)	Norfolk, UK	2

from a t-table, s^2 is variance of the population and d is the tolerated difference between sample and population means, i.e. allowable error. The estimation of n clearly depends on the amount of variation inherent in precipitation. This is normally not known, but can be estimated statistically from sample populations, i.e. from point rainfall readings. The amount of error which can be tolerated is determined beforehand. The advantage of Formula 4 is that it enables investigators to use about just the right number of gauges, not too few nor too many in order to achieve measurements within predetermined limits of accuracy. The limitation of Formula 4, on the other hand, is that it requires reliable information on the amount of variation in gross precipitation. In an attempt to overcome this problem, Helvey and Patric (1965 a and b) established a relationship between variation and mean raingauge catch. This is displayed in Figure 1. It has been suggested that information on variation can be extracted from this relationship as a first approximation until sufficient first hand data has been gathered (Toebes and Ouryvaev, 1970). Helvey and Patric (1965 a) suggested that, in most cases, a single raingauge would provide a satisfactory estimate of gross precipitation, but that more than one would increase the sampling accuracy.

I.2.1.2 Throughfall

As has been mentioned already, throughfall comprises rainfall that reaches the ground by both passing through the gaps in the forest canopy and by dropping off the leaves, twigs and branches that have been

<u>Figure 1</u> The Relationship Between Coefficient of Variation and Gross Precipitation. (After Helvey & Patric, 1965-b)



wetted previously by rain showers. A forest canopy is generally thought to be a rather uneven and complex structure with numerous branches and leaves. This makes it difficult to formulate and base the description of a forest canopy on rational and conceivable principles. Unless it is extremely well closed up, every forest canopy should have openings of varying sizes and gaps through which raindrops can pass directly without touching any vegetative obstacle. Since the sizes and the exact locations of these gaps and openings are unevenly distributed, the distribution of throughfall is affected as a result thereof. Added to this is the uneven and random distribution of water falling off the branches and leaves. All these represent a rather high variation in throughfall which has been reported by many investigators. Therefore, in throughfall measurements, the main concern is often to design a sampling procedure which ensures that all the variation is adequately sampled and explained. Such an approach is necessary in order to achieve accurate mean throughfall values for a given area of forest plot. In throughfall measurements, problems regarding point measurements and exposure can be considered trivial. Instead, what is important is the efficiency of sampling which is often controlled by the number of throughfall gauges and their total receiving area.

I.2.1.2.1 Instrumentation used in Throughfall Measurements

Various types of gauges have been used for throughfall sampling and they have not been standardized. Amoung the types are ordinary raingauges of various diameter, large troughs varying both in shape and dimension, plastic wedge-shaped gauges and various improvised gauges such as oil cans, stove pipes, funnels and large plastic sheets (Helvey and Patric 1965 a, Calder and Rosier, 1976). Since large numbers of gauges are often used in throughfall sampling, the use of proper raingauges is often not economical. Therefore, improvised gauges are commonly used for they are inexpensive. The purpose of employing troughs on the other hand is more technical rather than economical aiming to increase the gauge catching area, so that throughfall variation may be integrated.

I.2.1.2.2 Throughfall Measurement Problems

Owing to the high variation that has been mentioned already, the adequate measurement of throughfall presents rather involved sampling problems. Some difficulties arise from the consideration of the number of gauges needed to acquire reliable data, so that average throughfall for a given period can be estimated accurately. Other problems also arise regarding the question of how to choose gauge locations on a forest plot.

As to the number of throughfall gauges investigators, as in the case of gross precipitation cited earlier, have decided arbitrarily on the sampling size with which they measured throughfall. A list of some of the reported numbers of gauges is presented in Table 2 in a similar form to that of Table 1. It is clear from Table 2

Table 2 Number of Gauges Used by Various Investigators to Measure Throughfall.

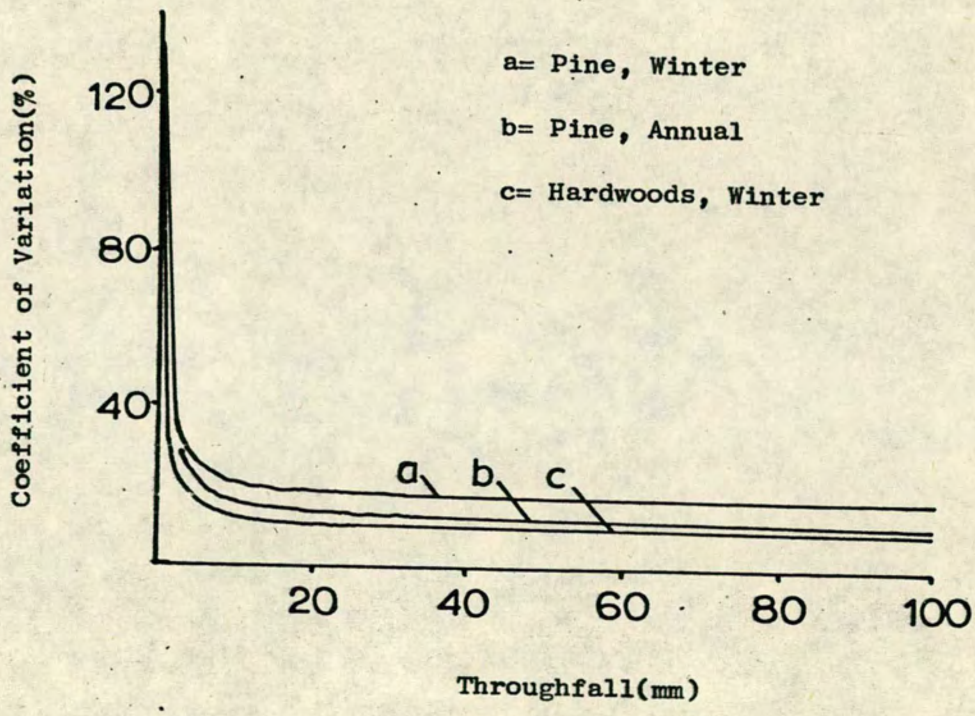
Reference	Country	Num. of Gauges
Wilm(1943)	Colorado, USA	1
Kimmins(1973)	Vancouver,Canada	2
Rothacher(1963)	Oregon, USA	4
Trimble & Weitzman(1954)	W.Virginia, USA	5
Singh & Szeicz(1979)	Canada	6
Law(1957)	Yorkshire, UK	10
Ovington(1954)	Kent, UK	10
Rogerson(1965)	Mississippi, USA	12
Rutter(1963)	Berks, UK	12
Jackson(1971 a and b)	Tanzania	20
Reynolds & Leyton(1963)	Oxford, UK	20
Carlisle et al(1965)	Lancashire, UK	20
Gash & Stewart(1977)	Norfolk, UK	24
Rowe & Hendrix(1951)	California, USA	24
Slatyer(1965)	N.Territory,AUSTR.	40
Ford & Deans(1978)	Scotland, UK	104
Brechtel(1965),cited in Miller(1977)	—	1206

that large numbers of gauges,up to 1206, have been used in interception experiments. However, in many experiments, too few gauges have been used to meet study objectives (Toebes and Ouryvaev, 1970). To overcome this problem, Helvey and Patric (1965 b) suggested that formula 4 should be used in the same way as has been described in I.2.1.1.2 for gross precipitation. They similarly provided information on throughfall variation which is displayed in Figure 2. This data can be used as a first approximation until sufficient and more reliable first-hand data has been gathered.

It should be noted that the problem regarding the number of gauges to be used is linked with the consideration of choosing the most suitable type of gauge. However, no clear conclusion has been available as to whether a certain type can be considered to be superior to others. Reynolds and Leyton (1963), for example, used rectangular troughs (61 X 91.5 cm) and reported considerable improvement over 127 mm. standard gauges in terms of standard deviation of the mean throughfall estimates, i.e. a decrease from 12% to 6%. Helvey and Patric (1965 a), on the other hand, concluded from their analysis of the experiments reported in eastern U.S.A. that the number of gauges was more important than their size. In one case, they estimated that only 20% fewer troughs than standard gauges (203 mm. in diameter) were needed to achieve the sampling efficiency.

Once the type and the number of instruments have been decided, the only problem which remains is to choose adequate locations on the forest floor for installation. In most cases, gauge locations have

Figure 2 The Relationship Between Throughfall and Coefficient of Variation.
(After Helvey & Patric, 1965-b)



been chosen randomly by using various random sampling techniques (Wilm 1943, Ovington 1954, Law 1956, Rutter 1963, Carlisle et. al. 1965). Others have installed their gauges systematically in a certain pattern such as on a grid or on straight lines radiating from tree trunks in order to detect any pattern of throughfall distribution in relation to the position of the tree trunks (Voigt 1960, Ford and Deans 1978).

It has been said already that many gauges are often needed to make accurate measurements owing to high variation in throughfall. In an attempt to reduce the number of gauges, Wilm (1943) introduced a different procedure which is often referred to as "the method of roving gauges". Studying the effects of thinning on net precipitation in Lodgepole pine (Pinus contorta latifolia), Wilm (1943) employed only one 203 mm. raingauge in each of his 2.5 acre half-plots. The gauge on a half-plot was moved after each storm to one of 12 points which had been selected randomly. Thus, 12 storms gave one complete circuit of all locations in a half-plot. He also moved his gross precipitation gauges after each storm to a new forest opening nearest to the corresponding throughfall gauge. This method has been realized as an adequate approach to reduce the number of gauges and, at the same time, to explain most of the throughfall variation over a long period of time. It does, however, have the limitation of not revealing the variation belonging to a single storm. Therefore, the method is recommended only where such information is not required (Reynolds and Leyton 1963). Otherwise, the method of roving gauges has been reported to give good estimates of mean throughfall values and has been widely used by many investigators (Law 1956, Rutter 1963, Rothacher 1963, Rogerson 1963).

I.2.1.3 Stemflow

Separate measurements of stemflow have been reported in the literature by means of stemflow gauges, otherwise known as stemflow collars or gutters. Collars have been made up out of various metal and rubber strips. Horton (1919), for example, used lead gutters attached to the trees, whereas Voigt (1960) and Rothacher (1963) used aluminium sheets in their stemflow gauge construction. Ovington (1954), on the other hand, constructed his collars with cotton wool that held stemflow water. Gauges of polyurethane foam have also been used (Likens and Eaton, 1970) as have expanded mastik strips (Ford and Deans, 1978). It is evident from the literature that, although many different materials have been employed, the method of measuring stemflow has been essentially the same in almost every case. Firstly, a stemflow gauge is expected to be sealed absolutely water-tight. Ford and Deans (1978) checked this by the change in bark colour. While the bark above the gauge became darker with wetting by rain, the bark below remained the same in colour, indicating a perfect sealing. Another important point that should be observed during installation of a stemflow gauge is to optimize the width of the gap between the gauge and the tree surface, so that no stemflow water overflow or any direct throughfall is received. Water diverted in the gutter is often led into a collector where it is measured by volume. The value obtained is then converted into milimetre depth over the tree projection area.

Sample trees on which stemflow is measured have often been chosen randomly (Rutter 1963, Orr 1972). Rothacher (1963), on the other hand, selected his sample trees from a wide range of tree diameter classes to represent the whole forest. Helvey and Patric (1965 b), however, suggested that measurement of stemflow on all trees on randomly located small plots provided a better sampling technique than that of individual trees. They recommended that the diameter of a plot should be about 1.5 times the largest tree crown or 20 m^2 in an area of small trees. By using plots instead of randomly selected single trees, it has been suggested that high variation found in stemflow between the trees could be integrated considerably.

Investigators have measured stemflow on various numbers of trees, generally arbitrarily chosen. A list of the number of gauges reported in the literature is given in Table 3. The number varies from 3 to 29. However, it is natural that Formula 4 can also be used to estimate the number of stemflow sample trees in order to achieve accurate measurement at a preselected probability level. Since stemflow has been reported to be highly variable. Formula 4 may estimate a very large number of gauges. Nevertheless, this can be avoided by tolerating greater error limits because stemflow often comprises a minor part of the net precipitation in a forest.

Table 3 Number of Trees on which Stemflow has been Measured by Various Investigators.

Reference	Country	Num. of Trees
Thorud(1963)	Minnesota, USA	3
Skau(1964)	Arizona, USA	3
Ovington(1954)	Kent, UK	5
Slatyer(1965)	N.Territory,AUSTR.	5
Gash & Stewart(1977)	Norfolk, UK	5
Carlisle et al(1965)	Lancashire, UK	7
Voigt(1960)	Connecticut, USA	7
Singh & Szeicz(1979)	Canada	9
Rothacher(1963)	Oregon, USA	10
Orr(1972)	S.Dakota, USA	10
Rutter(1963)	Berks, UK	18
Jackson(1971 a and b)	Tanzania	20
Reynolds & Leyton(1963)	Oxford, UK	20
Rowe & Hendrix(1951)	California, USA	29
Ford & Deans (1978)	Scotland	10
Law (1957)	Yorkshire, UK	5

I.2.2 The Other Methods of Interception Measurement

I.2.2.1 Floating Lysimeter

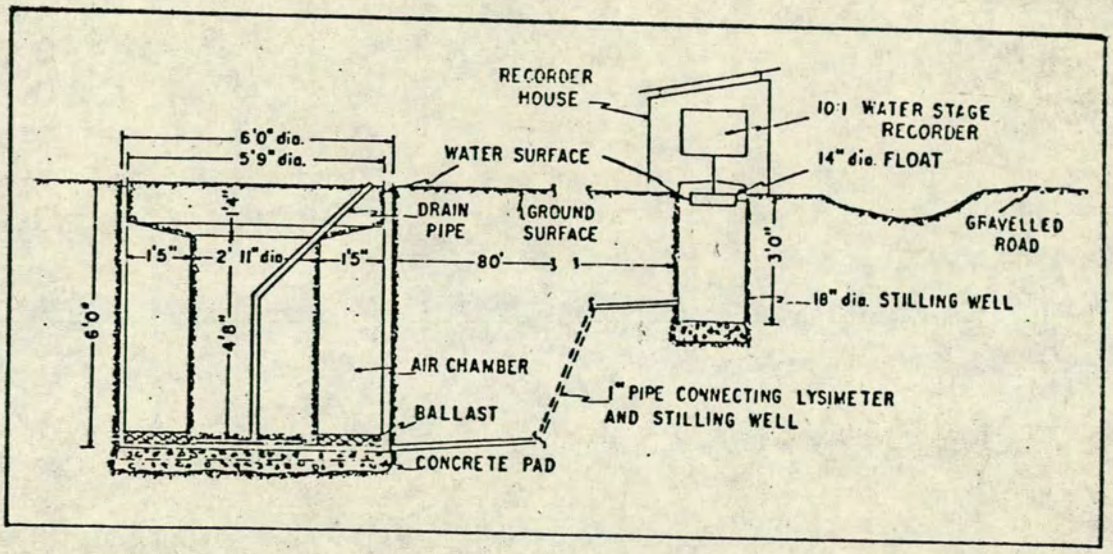
Lysimeters are multi-purpose instruments for the study of several phases of the hydrological cycle, e.g. infiltration, run-off and evaporation (Unesco, Glossary of Hydrology). We know from the work of McMillan and Burgy (1960) that lysimeters can also be used successfully in experiments on interception.

McMillan and Burgy (1960) constructed and installed two 183cm. diameter floating lysimeters in a field of perennial rye grass. Each lysimeter consisted of an outer tank (183cm. diameter) and an inner tank (180cm. diameter) depicted in Figure 3. The lysimeter was constructed in such a way that the inner tank floated on the water. The evaporation from the water between the two tanks was minimized by use of petroleum. Any change in the weight of the lysimeter resulted in the rise of the water level. The water level was measured automatically by means of a recorder connected to the lysimeter by a length of pipe 25mm. in diameter.

The use of lysimeters to detect water losses due to interception was based on artificial wetting treatments which were applied to one lysimeter at a time. However, wetting was applied alternately to each lysimeter so as to maintain similar soil moisture conditions. The differences in total water loss between wetted and dry lysimeters were attributed to net interception loss. It should be emphasized here that

<u>Figure 3</u> The Design of a Floating Lysimeter.

(After McMillan & Burgy, 1960)



only net interception loss, as defined by Burgy and Pomeroy (1958), is studied by this method. The results obtained from the experiments of McMillan and Burgy (1960) showed that total water loss from a wetted lysimeter did not differ from that of a dry one. This indicated that no net interception took place in perennial rye grass.

Generally, a major problem in working with a lysimeter is to ensure that vegetative and soil conditions in the lysimeter are truly representative of natural undisturbed conditions prevailing in the area concerned. However, criticism on such lines may not apply to the experiments described above because the artificial wetting was applied alternately so as to maintain similar soil conditions in both lysimeters. Also, the assessment of the interception losses was based on the comparison of the wet and dry lysimeter plots, but not on the actual absolute values of evapotranspiration. Therefore, although actual evapotranspiration values obtained may not be representative of the crop surveyed, the comparison between the two lysimeter plots is still valid.

Floating type lysimeters are constructed in small sizes and, therefore, suitable only for experiments with grass and other short crops. It is not really practical to use them in experiments with forest trees.

I.2.2.2 Natural Lysimeters

A piece of forest land on an underlying impermeable layer of clay can be likened to a lysimeter and called a "natural lysimeter".

Natural lysimeters, like the other types, can be used in interception studies. This has been exemplified by Law (1957) and Calder (1976).

Calder (1976) conducted his waterbalance experiments in Central Wales. A natural lysimeter with an area of $84m^2$ was used. The lysimeter comprised 26 Norway Spruce trees approximately 10m. in height. A diagram of the vertical section of the lysimeter is shown in Figure 4. It was surrounded by a drainage ditch which was dug as deep as the underlying clay layer. This clay layer was assumed to be impermeable and, therefore, served as the bottom of the lysimeter.

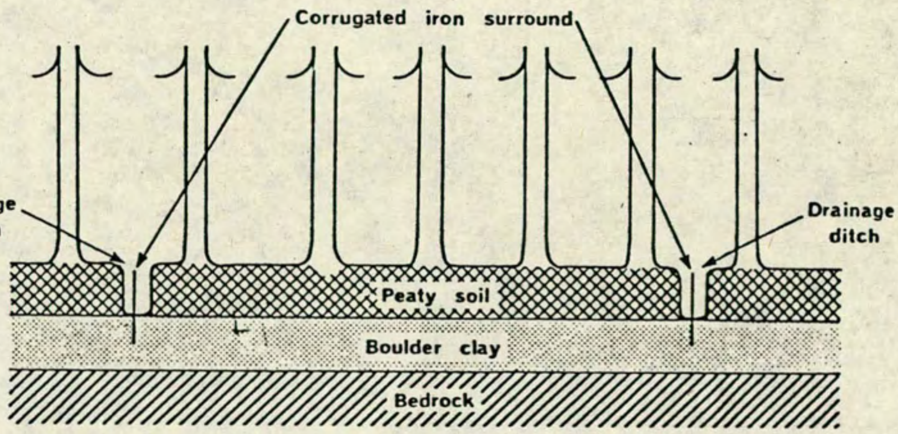
Evapotranspiration from the lysimeter was determined by solving the water balance equation given as:

$$\overline{\Delta S} = N - D - L - E_t \qquad \text{Formula (5)}$$

where $\overline{\Delta S}$ is the change in soil moisture content which was measured by a neutron probe, N is the net precipitation that was sampled on an adjacent plot by means of large plastic sheets described by Calder and Rosier (1976), D is drainage from the lysimeter as measured with a large tipping-bucket gauge, L is the leakage into or out of the lysimeter which was considered to be negligible, and finally E_t is actual evapotranspiration, i.e. evaporation from soil surface plus transpiration through the 26 trees confined in the lysimeter.

Law (1957) also described a natural lysimeter 0.111 acres in area installed in a stand of Sitka Spruce in the Hodder Catchment, Yorkshire. The lysimeter had a diamond shape and was surrounded by a wall sunk

Figure 4 The Construction of a Typical Natural Lysimeter.
(After Calder, 1976)



down into an underlying impervious clay strata. Run-off was measured from the lowest corner of the lysimeter and led by means of a pipe into a large storage tank where it was stored and measured.

Although a natural lysimeter is not primarily a method of interception, its use in combination with measurements of net precipitation appears to be of special value in determining interception loss from forests. Such a combination of experimental work enables investigators to study and assess the interception loss in a context of water balance of the forest. On the other hand, the method may be criticized on the basis that it assumes perfect impermeability of the clay bottom layer, whereas some leakage may occur through this layer. When such leakage (L) is ignored, evapotranspiration (E_t) is overestimated.

I.2.2.3 Experiments with Grass grown in a Nutrient Solution

An entirely different experimental method was successfully used by Burgy and Pomeroy (1958) in order to separate transpiration from interception, thus providing an estimate of net interception loss. They grew four small plots of various grasses in nutrient solution pans which constantly rested on ordinary checkout scales. By this method, the complicated measurement of soil moisture content was avoided. The grass plots were actually grown on packed exelsior which was sandwiched by hardware cloth and cheesecloth; the side walls being an aluminium frame. The method was based on the artificial wetting of a plot while another identical plot was left dry and transpiring. Total addition of water and a total amount of water loss

Such plants not same as natural ones

was recorded. Any difference in water use detected between wet and dry plots in laboratory conditions was attributed to net interception loss. However, as has been alluded to earlier, no net interception was measured in this experiment because both evaporation from intercepted water, i.e. wetted plot and transpiration from dry grass, occurred at similar rates. Therefore, interception loss was fully compensated by the suppressed transpiration while the leaves were wet.

Burgy and Pomeroy (1958) were also able to measure the interception storage capacity by a small modification of their identical equipment. A stilling well with a submerged point gauge was connected to one of the weighing pans. The initial depth of the solution in which plants were grown was determined by this point gauge prior to the artificial wetting. Then wetting was carried out and the net precipitation was removed from the pan to restore it to the original level of the solution. Storage capacity was then determined by the difference in weight of the plot before and after the wetting treatment. It was expressed as water depth over the plot area.

I.2.2.4 Experiments with Detached Tree Seedlings

Grah and Wilson (1944) described a technique involving measurement of the maximum surface detention of water. 18 Monterey Pine trees of 1-2 transplant stock from nursery beds and 17 Baccharis, an evergreen shrub, 1 to 4 years old were used in their experiments. Each plant was suspended from a balance in a sheet metal chamber of 61cm. diameter and

91.5cm. tall. The plant was then subjected to a gentle and uniform water spray. The plant was accurately weighed at one minute intervals from the beginning of the spraying onward. Spraying went on to the point where a maximum constant weight was observed. The maximum surface detention was then determined by subtraction of the initial weight from the final maximum weight recorded.

The method can be criticized because the plants used in the experiments are not connected to the soil moisture that would otherwise exert varying stress on the plant (Zinke, 1967). In addition, since the experiments were carried out in still air conditions, it may not be possible to extend the results to natural windy conditions.

I.2.2.5 Meteorological Methods

Penman has constructed an empirical formula, known as the Penman Formula, based on meteorological observations to determine evaporation from short grass with an unlimited water supply. Full details of the description and derivation of the formula has been described in various papers by Penman in the late 1940's and early 1950's, as well as in many other publications and textbooks (Penman 1963, Ministry of Agriculture Technical Bulletin No. 16, Ward 1975). The formula is a combination of the energy balance equation and the aerodynamic equation, given as:

$$E = (\Delta/\gamma\ H + Ea)/(\Delta/\gamma + 1) \qquad \text{Formula (6)}$$

where E = evaporation (mm/day)

Δ = the slope of the saturated vapour pressure (mbar K^{-1})

γ = the psychrometric constant (mbar $^{o}K^{-1}$)

H = the net radiational energy ($W\ m^{-2}$)

E_a = an expression for the drying power of the air involving wind speed and saturation deficit (mm/day)

Formula 6 has been used successfully in determination of evaporation from short grass in Britain. However, it is not suitable for forests. This is because the forest often presents an aerodynamically rough surface, thus transportation of water vapour is fast. Transpiration from a forest, on the other hand, is limited by the rate at which the vapour can diffuse through the stomata in the leaves; whereas grass shows little resistance to transpiration of water. For this reason, a variation of Formula 6 has been devised by Monteith, which is often referred to as the Penman-Monteith formula, for determining evaporation from forests:

$$\lambda E_T = [\Delta A + \rho Cp(VPD)/ra] / [\Delta + \gamma\{1 + (r_s/rq)\}] \qquad \text{Formula (7)}$$

where A = the available radiative energy ($W\ m^{-2}$)

p = the density of air ($kg\ m^{-3}$)

Cp = the specific heat of air at constant pressure ($J\ kg^{-1}\ K^{-1}$)

λ = the latent heat of vaporization of water ($J\ kg^{-1}$)

VPD = the vapour pressure deficit (mbar)

r_a = the aerodynamic resistance (sm^{-1})

r_s = the surface resistance (sm^{-1})

Formula 7 estimates evaporation from a dry forest canopy. When the canopy is wet r_s is zero and intercepted water evaporates at a higher rate. The evaporation equation for wet forest canopy becomes:

$$\lambda E = [\Delta A + \rho C_p (VPD)/r_a]/(\Delta + \gamma) \qquad \text{Formula (8)}$$

Rutter (1968) suggested the expression for net interception after Burgy and Pomeroy (1958) can be written as:

$$I(E_I - E_T)/E_I \quad \text{or} \quad (I - E_T/E_I)I \qquad \text{Formula (9)}$$

where I is interception, E_T transpiration rate and E_I is the rate of evaporation of intercepted water.

When Formulae 7 and 8 are placed in Formula 9:

$$E_T/E_I = \frac{\Delta + \gamma}{\Delta + \gamma[(r_a + r_s)/r_a]} \qquad \text{Formula (10)}$$

$$(I - E_T/E_I)I = \frac{\gamma r_s I/r_a}{S + \gamma[(r_a + r_s)/r_a]} \qquad \text{Formula (11)}$$

Net interception loss may be written:

$$\frac{\gamma r_s I}{(S + \gamma)r_a + \gamma r_s} \qquad \text{Formula (12)}$$

It is clear from the above formulae that the determination of the rate of transpiration from a dry forest canopy and the rate of evaporation of intercepted water from wet canopy requires labour intensive meteorological observations such as radiation energy, wind speed and moisture content of the air. The method also necessitates highly sophisticated and expensive instrumentation with which the meteorological variables can be measured at short intervals and automatic data acquisition can be achieved. Needless to say, on the other hand, the use of the meteorological method has contributed immensely to knowledge of the physical mechanism of evaporation of water. The method has also been used in interception experiments to determine the rate of evaporation of precipitation water intercepted by forest canopy (Stewart 1977, Singh and Szeicz 1979, Murphy and Knoerr 1975, McNaughton and Black 1973, Rutter et. al. 1972).

1.2.3 Discussion

It is apparent from the preceding discussion that each method described has its advantages and disadvantages. There arises, therefore, the problem of choosing the most appropriate method for any particular investigation. The traditional method, for example, is labour intensive and, although it accurately measures interception loss, it does not really explain the physical processes involved. The micrometeorological approach, on the other hand, is primarily concerned with the meteorological factors determining the evaporation of intercepted water, but it is not suitable for investigation of such features such as canopy storage and species variation in the interception value. Micrometeorological observations also have the disadvantage of requiring very sophisticated and expensive instruments. The methods designed for grass and small trees are not suitable for experiments with grown forest trees. They include, for example, the lysimeter approach adopted by McMillan and Burgy (1960) and the laboratory techniques devised by Burgy and Pomeroy (1958) and Grah and Wilson (1944). A natural lysimeter, on the other hand, does not really provide a method by which interception by forest canopy can be detected from other sources of water loss, such as transpiration by trees and evaporation from soil.

These problems have been realized and, in recent experiments, a combination of more than one method has often been used to combine their advantages and, thus, to overcome their limitations. In the Thetford experiments, for example, both the traditional method and micrometeorological observations have been employed. In the Hafren experiments, interception was investigated by means of a natural lysimeter and simultaneous measurement of net precipitation. By such combinations, the accuracy with which interception was measured and the human understanding of the process have both been increased.

Serious thought was given to the use of a combination of the traditional method and micrometeorological observations for the present work. But this had to be ruled out because of lack of equipment and the limited time in which the work had to be completed. This approach was also impossible from the point of view of requiring team work as opposed to that of a single research worker. On the balance, it was decided to employ only the traditional method. However, it was also considered that some supplementary techniques could also be used for short periods of time.

PART II

II.1 DESCRIPTION OF THE EXPERIMENTAL SITE AND ITS CLIMATE

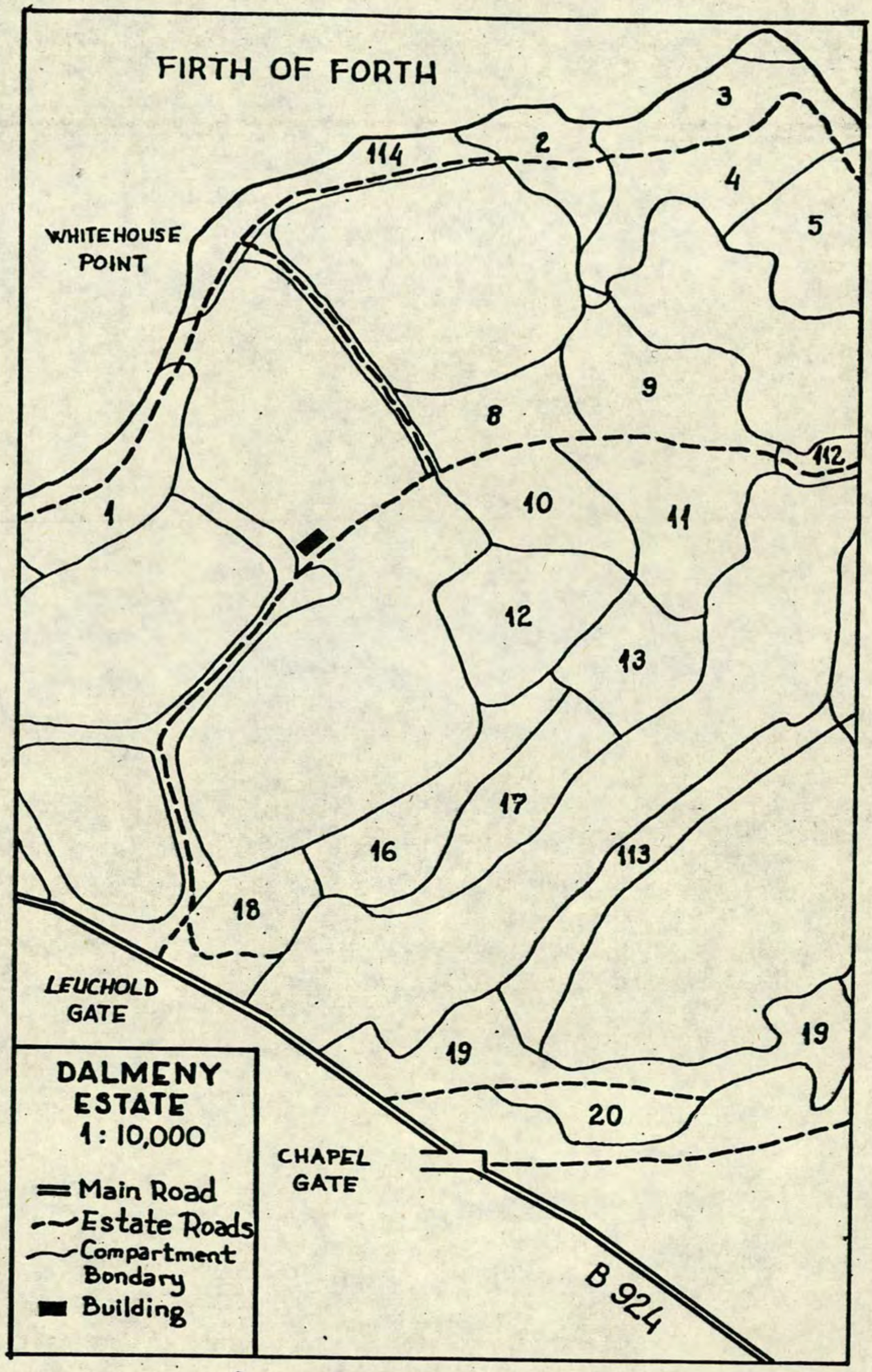
II.1.1 The Location

The experimental field work was carried out in Dalmeny Estate in West Lothian region. Dalmeny Estate is a dedicated woodland owned by Lord Rosebery. Although it is open to the public, it nevertheless provides almost complete security for experimental instrumentation and apparatus. The Estate is situated in the triangle bounded by the River Almond, the main road to South Queensferry, that is the B924, and the foreshore of the Firth of Forth. Figure 5 shows a part of this area. The 6" to 1 mile maps of the area are NT 17 NW and NT 17 NE. The geographical coordinates are approximately 55° 59' 30" N and 03° 21' 25" W. The location of the Estate on the outskirts of Edinburgh affords easy access to a research worker based in the city.

About 275 ha. of the Estate is forest. The Estate also consists of arable land and serves as a hunting ground, particularly for pheasants. The woodlands are composed of numerous tree species with various age classes, thus providing a suitable site for meeting the aims of the project.

The Estate lies between the altitudes of sea level and 119m. Although all aspects are represented and slopes vary from very steep to flat, the area in general is not noticeably rugged. The hill tops

Figure 5 Map Showing Part of the Dalmeny Estate near Edinburgh Where the Experiment Was Undertaken.



and ridges consist of basaltic outcrops which intrude through the main carboniferous strata. The majority of the soils are dark loams of a loose texture and vary in depth.

II.1.2 Climate of the Experimental Site

The climate of the area is a part of the general typical climate over the coastal areas of eastern Scotland. Dalmeny Estate is situated on the coast of the Firth of Forth, which is a dominant feature of the area. In this section of the thesis, the intention is not to give full details about the climate because many of the meteorological elements of the climate may not be closely relevant to the general theme. However, the prime factors affecting the distribution of precipitation should not be passed uncited. Among these are the incoming solar radiation as sunshine hours, speed and direction of prevailing winds, air temperature, fog and mist, precipitation and water balance of the area. Below is a short review of this information in the form of the long term averages. However, information on the past precipitation record for the region will be receiving special attention. This is because of the significant role of the distribution and general pattern of precipitation, rain in particular, in the study of interception. Most of the information cited has been taken from Plant (1968), whose description of the local climate is based mainly on data for Turnhouse Airport which is only about 5 km. from the experimental area.

II.1.2.1 Air Temperature

Plant (1968) reports that the winter temperatures in the region are comparable with those of London and the east coast of England. This is because of the moderating influence of the North Sea, whose surface temperature in winter remains higher than the ground surface temperature over the adjacent land areas. In summer, on the other hand, this moderating influence is no longer at work. Instead, the effect of latitude on the solar energy received becomes the dominant factor controlling temperature. As a result, summer temperatures are several degrees lower than they are in the south of England. Table 4 gives the long term average values of maximum, minimum and mean temperature at Turnhouse Airport. The average of daily maximum temperature is highest in July with 18.9°C and the minimum temperature for January is the lowest. On the whole, July and August are the warmest months in terms of daily mean temperature, that is 15°C for both of these months.

II.1.2.2 Sunshine Hours

Table 5 shows 30 year average values of sunshine hours as monthly totals and daily means. From these figures, Plant (1968) concludes that the annual total sunshine in hours for the Edinburgh area is on average comparable to that for example the London area, being just over 1300 hours per year. It is apparent from Table 5 that most of this total belongs to the summer months; during winter, the daily mean sunshine period is as small as 1.53 hours for January and 1.17 hours for December.

Table 4 Long-Term Temperatures for Turnhouse Airport (°C)

(After Plant, 1968)

	Max.	Min.	Mean
Jan.	5.6	0.0	2.8
Feb.	6.7	0.3	3.3
Mar.	8.9	1.7	5.0
Apr.	11.5	3.1	7.2
May	14.4	5.6	10.0
June	17.2	8.9	12.8
July	18.9	10.5	15.0
Aug.	18.2	10.0	15.0
Sep.	16.1	8.3	12.2
Oct.	12.6	6.0	8.9
Nov.	8.9	2.8	6.1
Dec.	6.7	1.7	4.4

Table 5 Average Sunshine Durations at Turnhouse Airport for 30 Years from 1931 to 1960. All in Hours. (After Plant, 1968)

	Sunshine Hours	
	Monthly Total	Daily Mean
Jan.	47	1.53
Feb.	71	2.53
Mar.	101	3.26
Apr.	142	4.72
May	181	5.85
June	183	6.09
July	159	5.14
Aug.	135	4.36
Sep.	119	3.96
Oct.	87	2.79
Nov.	54	1.81
Dec.	36	1.17
YEAR	1315	3.60

II.1.2.3 Wind

Wind direction frequencies for Turnhouse Airport show that 45 - 50% of all winds blow from directions in the quadrant between south and west. However, a remarkably high frequency of winds from between north-east and east is commonly observed in the spring and early summer (Plant, 1968).

As to wind speed, Plant (1968) considers Turnhouse as a location where south-westerly surface winds are abnormally strong. He also considers that exposed places along the Forth coastline experience easterly winds much higher than those recorded at the Airport. Abnormally strong winds have also been recorded on the Forth Road Bridge, which is only 1.5km from the experimental site.

II.1.2.4 Fog

Fog at Turnhouse is recorded for the purpose of aviation. Thus the criterion used to define it is visibility. Fog is said to occur when the visibility falls to below 1006m., "thick fog" and "dense fog" occur when the visibility is less than 201m. and 50m. respectively. Data for the 10 year period from 1958 to 1967 for Turnhouse Airport can be seen in Table 6.

If the water content of air during fog can be directly related to the level of visibility, it would probably be concluded that thick

<u>Table 6</u> **Average Number of Hours with Fog at various densities at Turnhouse Airport for the Period of 1958-1967. (After Plant, 1968)**

	VISIBILITY		
	1006 m.	201 m.	50 m.
Jan.	28.1	8.7	0.4
Feb.	29.2	11.1	1.5
Mar.	10.7	2.3	0.2
Apr.	12.3	3.7	0.3
May	12.0	1.3	0.1
June	30.8	6.8	0.2
July	11.0	0.8	0.0
Aug.	6.9	1.7	0.1
Sep.	20.1	8.9	0.7
Oct.	36.7	13.2	1.6
Nov.	40.4	16.3	3.6
Dec.	37.0	18.7	2.6
YEAR	275.2	93.5	11.3

fogs are those most likely to be of hydrological significance. Table 6 shows that such fogs occur on average only 11.3 hours a year. Plant (1968) reports that most fogs in the area do not last on average more than 3 hours, and furthermore that they generally occur on days with no wind and calm weather. The information on fog in the area appears to suggest that the ideal conditions for "fog drip" to take place in the local woodlands are not perhaps fully met.

II.1.2.5 Precipitation

According to Plant (1968), the average rainfall for the area is well below the average for the United Kingdom as a whole. It can be seen from Table 7 that the annual rainfall is 716.1mm. at the rainfall recording station of Dalmeny House on Dalmeny Estate and 684.9mm. at Turnhouse Airport. The annual rainfall is uniformly distributed through the year. Rains of high intensity appear to be less important than they are, for example, in the upland parts of Scotland. Therefore, prolonged and heavy rain is not a typical feature of the rain climate of the area. Rain falls quite frequently as small volumes. Heavier rains occur in late summer, particularly in August which is the wettest month. Another feature of rain climate of the area is "driving rain". Plant (1968) reports that it is common at Turnhouse Airport for rain to fall in association with strong winds. An example of a most severe driving rain occured on 21st October 1963 when 8.3mm. of rain was recorded in association with a mean wind speed of 23 mph. and lasted only one hour. It appears that driving rain might especially

Table 7 Average Rainfall (mm) at Turnhouse Airport and Dalmeny House for the Period of 1916-1950 .
(After Plant, 1968)

	Dalmeny House	Turnhouse Airport
Jan.	64.8	61.7
Feb.	44.2	41.9
Mar.	43.2	39.6
Apr.	42.2	40.4
May	55.9	54.9
June	50.6	47.2
July	75.4	73.9
Aug.	82.3	78.7
Sep.	67.8	64.5
Oct.	73.4	70.6
Nov.	63.0	60.2
Dec.	53.3	51.3
YEAR	716.1	684.9

be considered as an important feature in relation to interception.

The average number of days of snowfall or sleet is 30 days per year. The equivalent of this snow averages about 5mm. and is, therefore, only a small fraction of the total annual precipitation.

II.1.2.6 Water Balance

The water balance of the southern part of Scotland has been studied by Ledger and Thom (1977) by utilizing the long term historical hydrological data recorded at the Royal Observatory, Blackford Hill in Edinburgh, which receives rainfall of similar order to Turnhouse Airport and Dalmeny House. Ledger and Thom (1977) report that a substantial moisture deficit occurs during the summer. Generally, the water deficit period starts in March or April and continues until October or November, reaching a maximum level of over 100mm. in most years. The mean annual maximum potential deficit for the area is 123mm. More information can be seen in Table 8 which gives monthly potential moisture deficit data both for a typical year and for the period 1916 - 50. Ledger and Thom (1977) also reported that prolonged and extreme maximum potential water deficit periods could be expected to occur in the area once in about 40 - 50 years on average.

II.1.3 Description of the Forest Plots

The woodlands on the Estate are plantations that have been

Table 8 Potential Moisture Deficit at Blackford Hill.(All in mm.)

(After Ledger and Thom,1977)

	J	F	M	A	M	J	J	A	S	O	N	D
For a Typical Year (1967)												
Actual Precipitation	37.2	75.0	37.9	9.9	114.6	16.6	50.2	55.0	63.4	101.7	45.5	29.9
Mean Potential Evaporation	0.0	9.0	28.3	51.6	78.8	87.8	82.8	65.9	41.4	20.6	3.9	0.0
Surplus Precipitation	37.2	66.0	9.6	-41.7	35.8	-71.2	-32.6	-10.9	22.0	81.1	41.6	29.9
Cumulative Deficit	-	-	-	41.7	5.9	77.1	109.7	120.6	98.6	17.5	0.0	0.0
For the Period 1916-50												
Mean Rainfall	62	43	41	41	56	48	77	80	65	72	61	53
Mean Potential Evaporation	0	9	28	51	79	88	83	66	41	21	4	0
Cumulative Deficit	0	0	0	10	33	73	79	65	41	0	0	0

planted in various years during the period from the second half of the last century onwards. They are divided into many small compartments, each about 3 - 5 ha., for forest management purposes. The compartments are uneven in terms of tree species and age classes, however they mostly comprise small areas of uniform forest types. The species are:

Scots Pine (SP)	- Pinus sylvestris L.
Sycamore (S)	- Acer pseudoplatanus L.
Larch (La)	- Larix
Beech (Be)	- Fagus sylvatica L.
Elm (E)	- Ulmus spp.
Oak (O)	- Quercus spp.
Corsican Pine (CP)	- Pinus laricio (Poir.) Palibin
Norway Spruce (NS)	- Picea abies (L.) Karst
Ash (A)	- Fraxinus spp.
Lime (Li)	- Tilia spp.
Horse Chestnut (HC)	- Aesculus spp.

Among these species, the first 4 account for the most of the total timber volume of the Estate.

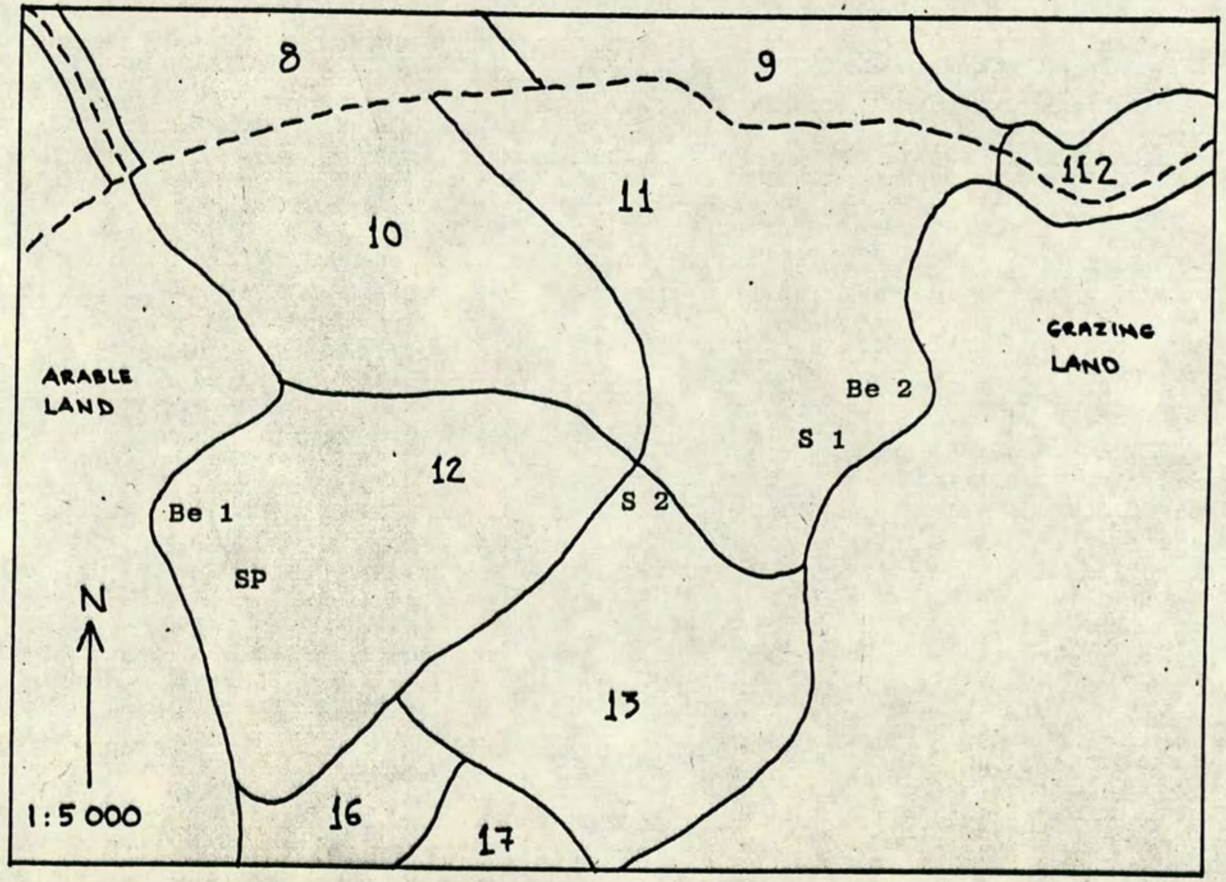
In order to find a suitable site for the present interception measurement, a careful reconnaissance work was carried out. Firstly, maps and air photographs of the area were studied and this study showed that the Estate consisted of various species which was a favourable feature from the standpoint of the aims of the present work to compare different species in terms of interception loss. Then, the woodlands were visited and carefully studied from various standpoints such as species, age classes, aspect and slope, access and logistics. Eventually, it was decided that those woodlands in compartments 11, 12 and 13 provided a favourable site because these compartments are situated in a small locality and comprise various tree species. They also provided a suitable site for installation and maintenance and logistics of the experiment. The structures and features of the plots are as follows:

Scots Pine (SP) Compartment 12 consists of a small mature Scots Pine stand with an area of about 2.20 ha. (Figure 6). It is situated on a gentle slope with a westerly aspect. The average height of the trees is about 12m. and the average tree diameter is 24cm. at breast-height (dbh). There are, on average, about 1750 trees per ha., so that the tree crowns cover the area quite closely. However, there are numerous small gaps between the crowns in the forest canopy. The depth of the canopy is about one third of the average tree height (= 4m.).

The stand is fully exposed to the westerly winds, which bring most of the local precipitation. It was, therefore, considered that edge effects could also be studied at this site along with the interception of precipitation.

Mature Beech (Be 1) This plot is also in Compartment 12 in the vicinity of the Pine described already. It consists of a group

Figure 6 Map Showing the Location of the Sites Where the Experiments were Conducted. SP= Scots Pine, Be 1= Old Beech, Be 2= Young Beech, S 1= Young Sycamore, S 2= Young Sycamore. Compartment Nos: 8 - 112 Compartment Boundary: ——
Road: ---



of very old Beech trees with a large inter-tree distance - about 400 trees per ha. The area is about 1.00 ha.; the Beech trees do not spread over the area uniformly. The average height is around 20m. with an average dbh of 55cm.

The canopy structure of the Beech tree shows a great contrast to the Pine, with the main branches (limb) being the dominant factor. The canopy closure is not complete and there are large gaps between and within the tree crowns.

The Pine and Beech sites were chosen and experiments were designed at these sites to provide information on interception, so that a species comparison would be possible since the two sites are in the same locality with the same exposure.

Young Beech (Be 2) A small young Beech plantation in Compartment 11 with an area of about 0.40 ha. was also chosen as an experimental site. The trees have been planted close to each other - about 4400 trees per ha. The crowns are very close and often overlap. The average tree height is about 5m. with an average dbh of 8cm.

Young Sycamore (S 1) In Compartment 11, a young Sycamore plantation neighbouring the young Beech described already was also used for the present experiment. The site occupies about 0.40 ha. consisting of trees of 6m. high with an average dbh of 9cm. The crowns build up a moderately close canopy with only small inter-tree gaps. On average, there are 4200 trees per ha. The site was chosen for comparing the results obtained from the young Beech (Be 2).

<u>Young Sycamore</u> (S 2) Another young Sycamore site was chosen in Compartment 11 (see Figure 6) surrounded by large mature deciduous trees in order to study the probable effect of sheltering and exposure on the amount of interception loss from this species. S1 is situated on the forest edge and, therefore, exposed to the east direction. It is a very small plantation with an area of 0.25 ha. The trees are identical to those in the young Sycamore site (S1) described earlier.

PART III

INSTRUMENTATION AND SAMPLING TECHNIQUES USED IN THE EXPERIMENTS UNDERTAKEN AND ACCURACY ANALYSIS

The purpose of this part of the thesis is two-fold.

Firstly, it describes the work involved in designing, constructing and calibrating various instruments used in the present experiments. It has already been shown that it is still not clear as to whether one particular instrument has superiority over others in measuring precipitation both in open field and under the trees. This problem is particularly marked in the case of throughfall measurements. For this reason, this section also reports on work undertaken to compare different types of instrumentation.

The second purpose of this section of the thesis is to describe how gross precipitation, throughfall and stemflow were sampled. This inevitably involved the problems of choosing sufficient sampling size (i.e. number of gauges) and of where and how to install the instruments.

It must be emphasized that to meet the objectives, it appears to be logical to describe the instrumentation and sampling techniques and, at the same time, to present the results of analyses made to reveal, for example, any advantages due to a particular instrument or the way it is installed. By far the most important of these analyses are those concerned with determining the number of gauges required to achieve a desirable accuracy of measurement. It may be thought that results of such analyses ought to be presented separately in a later section. However, a careful consideration of the present work as a whole suggested that it was more appropriate and more useful to present them in a part specifically devoted to methodology.

III.1 GROSS PRECIPITATION MEASUREMENTS AT THE EXPERIMENTAL SITE

The purpose of this section is, firstly, to describe the instrumentation used to measure the gross precipitation falling on the experimental site and, secondly, to discuss some statistical aspects of the sampling problems regarding the accuracy of the measurements of this variable. Although various types of gauges were used, it is convenient to study them in two groups:

i) Plastic funnel gauges (152mm. diameter).

ii) Other gauge types.

III.1.1 Plastic Funnel Gauges (152mm. diameter)

As shown in Plate 1 these gauges were hand-made. An ordinary annular plastic funnel with a diameter of 152mm. was used as the receptor. The vertical walls were sharpened to avoid the probable error that would have otherwise occurred. To construct a gauge, the plastic funnel was fitted inside a glass bottle with a rubber bung as shown in Plate 1. Rain water received by the plastic funnel was collected and stored in a glass bottle which had a volume of $1000cm^3$. It follows that the glass bottle was large enough to store 55mm. rainfall which was considered suitable for weekly readings.

When assembled, the gauges used were about 33cm. in height. When installing the gauge, the glass bottle was buried into the earth some 10cm. Thus, the rim of the funnel was 23cm. above the ground

<u>Plate 1</u> The Construction of a Home-Made Plastic Funnel Raingauge.

(1) Plastic Funnel, Diameter=152mm.

(2) Rubber Bung, Diameter=45mm.

(3) Glass Jar, Volume=1000cm^3

surface. This height was observed to be sufficient to prevent insplash of rain-drops (Green 1970 suggested a minimum height of 7.5cm). In the experimental site, the surrounding of the gross precipitation gauges was always short grass which must also have contributed considerably towards preventing insplash.

On the other hand, we know from Rodda (1967) that when installed at higher elevations above the ground, a raingauge measures less rainfall than what actually falls. This is due to the pronounced wind effect. Taking this aspect into account, the plastic funnel gauge's height (23cm.) ought to be small enough not to cause such reductions. This assumption appears to be fair when considering the fact that a 127mm. standard raingauge (British Met. Office. Mk. 2) is generally installed with its rim 30.5 cm. above the ground surface (Green 1970, Ward 1975).

Gross precipitation at the experimental site was measured at one week intervals. However, on some occasions, the interval was greater because the gauges were not read due to the rainfall that fell on the days scheduled for measurements. All readings were made on dry days so as to avoid any distortion of rainfall data.

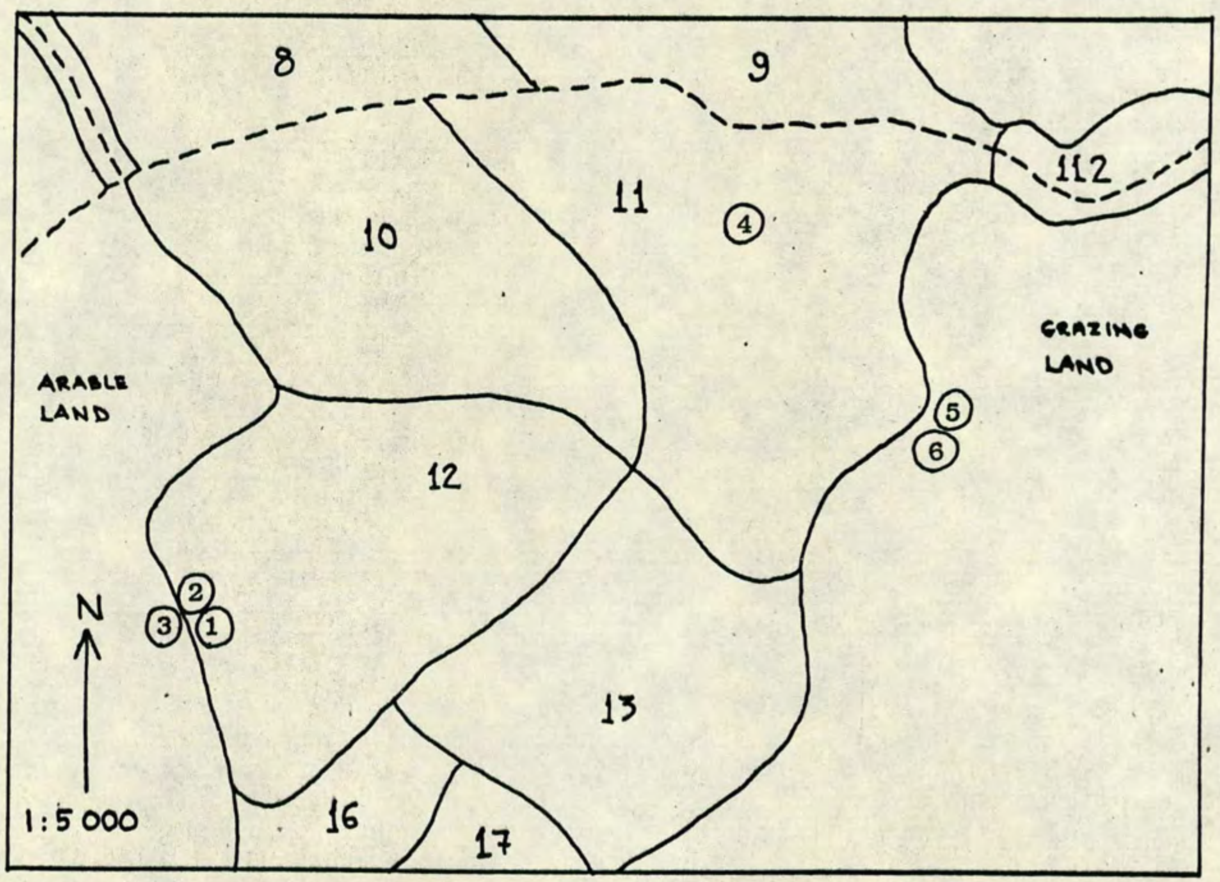
The weekly measurements were made by use of a specially calibrated glass tube which had a capacity of 7mm. rainfall. Rainfall depth was directly read from the measuring tube to the nearest 0.2mm. However, the weekly rainfall amounts, on many occasions, were much higher than 7mm. For this reason, a larger plastic tube with a capacity of 33mm.

rainfall was calibrated in accordance with the rim area of the 152mm. gauges. Rainfall readings in this tube were made to the nearest 0.5mm. To measure rainfall, the funnel of each gauge had to be removed and the water content had to be poured into the measuring tube. Then the funnel was inserted into the glass jar and installed in its original location.

To sample the rainfall over the experimental site, 3 plastic funnel gauges were initially installed on 6 May 1977 on the western boundary of Compartment 12. The location of these gauges is shown on the map in Figure 7 as numbers 1, 2 and 3. These 3 gauges served as gross rainfall gauges in connection with the measurement of throughfall in the Scots Pine of Compartment 12, which commenced at the same time. However, three weeks later on 26 May 1977, the gross precipitation sampling was extended by installing 3 more gauges of the same type. As can be seen in Figure 7 one of these gauges (No. 4) placed in the centre of a forest opening about 75m. in diameter in Compartment 11. The other 2 gauges (Nos. 5 and 6) were installed just outside Compartment 11 in grazing land. However, gauges 5 and 6 had to be abandoned on 6 July 1977 because they were continually disturbed by the livestock grazing there.

In selecting the locations of all 6 gross precipitation gauges considerable attention was paid to choosing sites where a laminar and undisturbed airflow might be expected to occur over them. This was achieved by the utilization of the natural configuration of the terrain instead of taking such measures as turf walls and wind shields which

Figure 7 Map Showing the Locations of the Plastic Funnel Gauges Used to Measure Gross Precipitation at Dalmeny. Gauge Nos: 1,2,3,4,5,6. Compartment Nos: 12. Road: --- Compartment Bondary ——



are both costly and difficult to install and maintain. Although employment of a ground-level gauge (pit gauge) would have been of special value in assessing the amount of rain in the area, this was not carried out for the same reasons. One other point borne in mind when locating the gauges was the necessity of ensuring measurements were not affected by neighbouring trees. The rule suggested by Helvey and Patric (1965 a) was observed, so that each gauge had 45° of clearance at its orifice.

As has already been mentioned, the intensity of sampling is an important factor determining the accuracy with which the precipitation falling on an area can be estimated. Formula 4 can be used to estimate how many raingauges should be employed to reach predetermined accuracy levels of mean rainfall. However, this formula requires information on the amount of variation involved in precipitation. Since such information was absent for the experimental site, the number of gauges was decided, in the first instance, according to the numbers used by various investigators listed already in Table 1 (I.2.1.1.2) and also according to the information provided by Helvey and Patric (1965 b) which has already been presented (Figure 1). Subsequently, however, analysis of a set of data collected between May and October 1977 indicated that weekly rainfall readings in the plastic funnel gauges did not differ significantly. The results of this analysis are given in Table 9. The values of sample standard deviation indicate that there are no significant differences in the weekly readings from the 152mm. gauges. The weekly readings from each gauge are given in columns 1 to 6. Figures in column 7 are arithmetic mean values; in column 8, standard deviation and in column 9 coefficient of variation. The figures in the last two columns (10 and 11) in Table 9 give the number of gauges estimated by Formula 4 for estimation of rainfall within $\pm$1mm.

Table 9 A selection of Gross Precipitation readings in Plastic Funnel Gauges during Summer 1977, and the Results of Preliminary Statistical Analyses.

(s=Standard Deviation, C.V.=Coefficient of Variation,%, all in mm.)

	Gauge No:									Num. of Gauges (Error=±1 mm.)	
Period	1	2	3	4	5	6	Mean	s	C.V.	P=0.95	P=0.99
19.5-26.5.1977	1.9	1.7	1.9	---	---	---	1.8	0.12	6.3	1	1
20.7-26.7.1977	9.0	9.0	9.5	9.0	---	---	9.1	0.25	2.7	1	1
14.7-19.7.1977	15.5	15.0	15.5	16.0	---	---	15.5	0.40	2.6	1	1
7.9-13.9.1977	20.0	20.0	21.0	19.0	---	---	20.0	0.82	4.1	3	5
21.9-29.9.1977	33.0	33.0	33.0	32.5	---	---	32.9	0.25	0.8	1	1
27.5-8.6.1977	35.5	35.9	35.9	36.8	34.3	35.7	35.7	0.81	2.3	3	5
9.6-23.6.1977	41.1	40.9	40.9	---	40.0	41.5	40.9	0.55	1.3	2	2
6.10-10.10.1977	54.5	54.5	54.0	55.5	---	---	54.6	0.63	1.2	2	3

limits for 95% and 99% probability levels, respectively. These numbers range from 1 to 5, which indicated that the initial sampling with 4 to 6 gauges was satisfactory.

A better estimate of standard deviation for given rain sizes could only be obtained after more data had been gathered. Such information is provided retrospectively in Figure 8 where standard deviation is plotted against mean weekly gross precipitation for all available 43 sets of weekly rainfall readings. An attempt was made to establish the relationship between standard deviation and gross precipitation and a linear regression equation and its line are given in Figure 8 A and a semilogarithmic equation and its curve in Figure 8 B. Although these two different methods yielded similar correlation coefficients (r), the curvilinear regression must be preferred because it appears to present the data scatter better, particularly for the greater values of gross precipitation. It should also be noted that this relationship is not affected by seasonal variations in dormant and growing periods.

The numbers of gauges required to achieve estimates of mean weekly gross precipitation within error limits of 5% and 10% at two probability levels of 99% and 95% have been calculated according to Formula 4. The standard deviation values required have been obtained by extrapolation of the semilogarithmic regression equation in Figure 8 B at various gross precipitation sizes (10, 20, 30, 40, 50mm.). The results of these calculations are shown in Figure 9, which indicated, once again, that the number of gauges used was satisfactory.

Figure 8 The Scatter Diagram of Standard Deviation of Mean Gross Precipitation at Dalmeny. Summer(•), Winter(○).

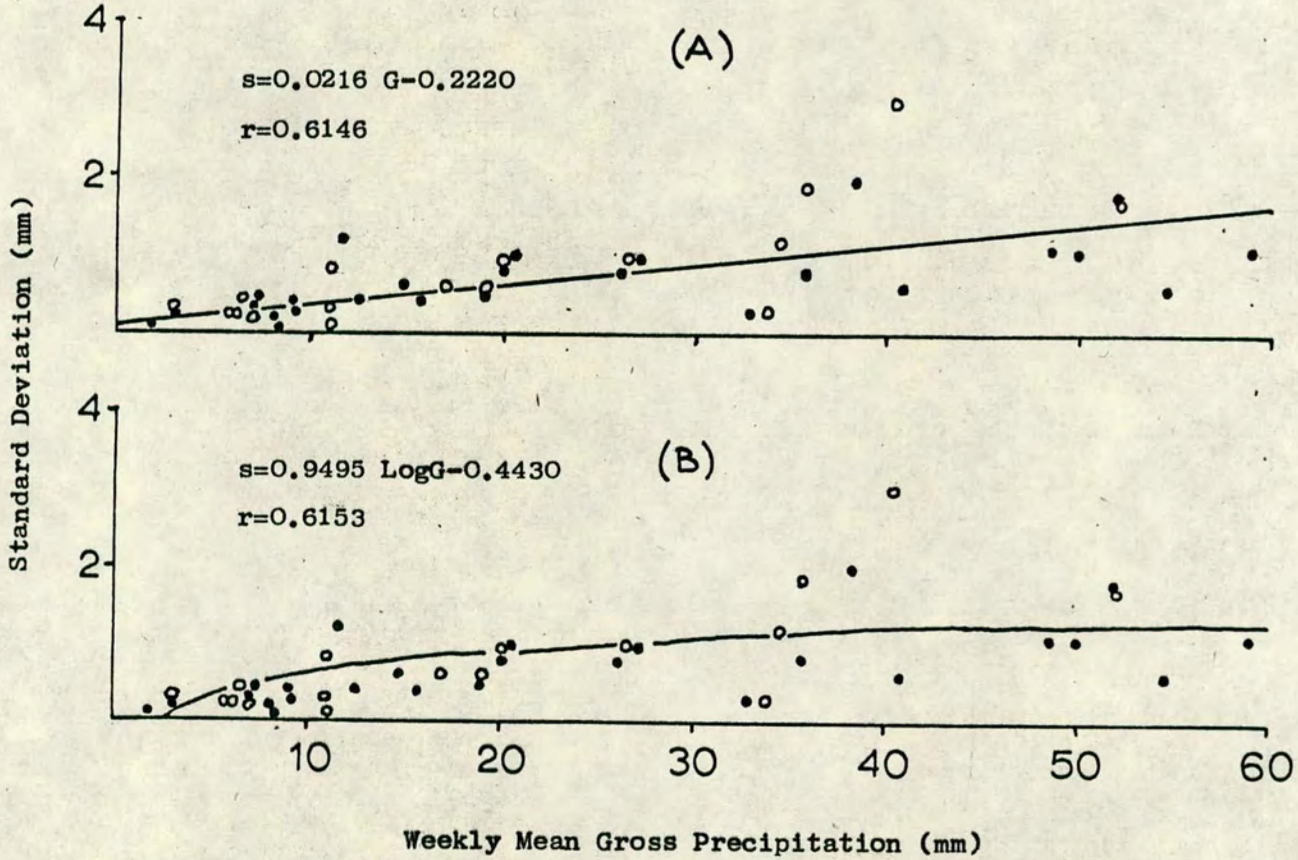
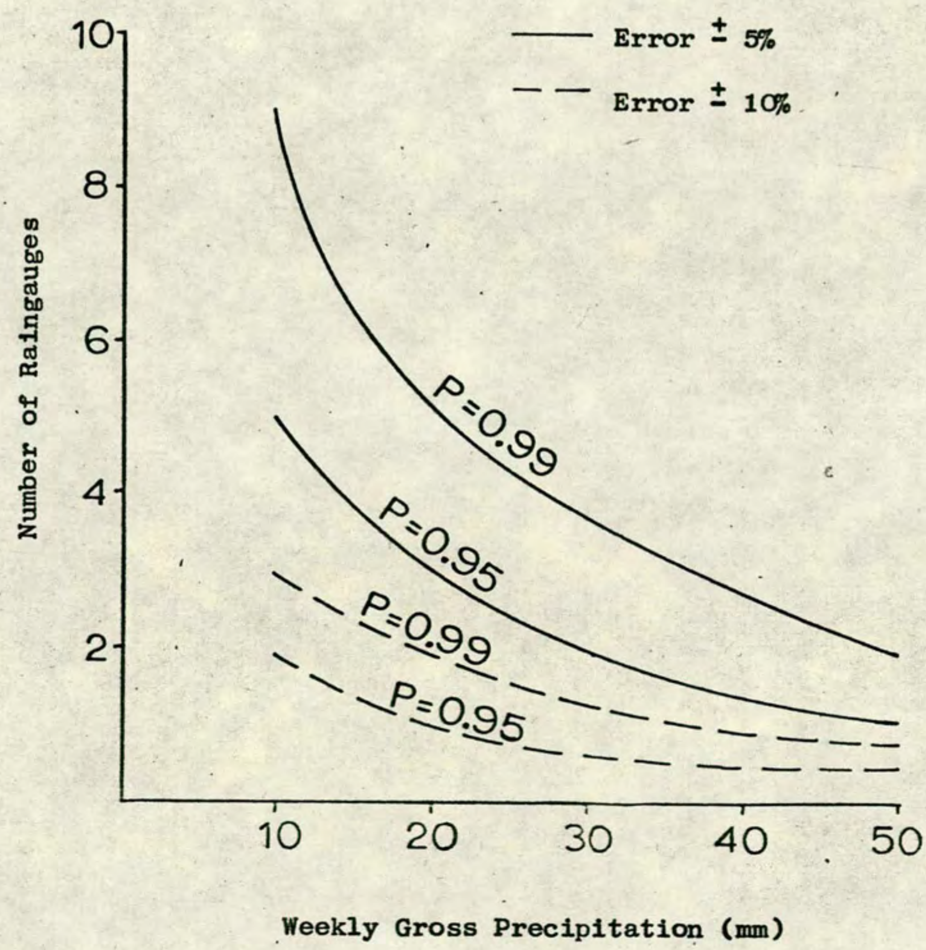


Figure 9 Numbers of Gross Precipitation Gauges Estimated by Formula 4.



III.1.2 Other Gauge Types

In addition to the 152 mm. funnel gauges, two further types of raingauge were also used in the experimental site to improve the sampling of gross precipitation and also to compare the readings from different types of gauges. These are:

i) 127mm. Standard Raingauge (British Met. Office Mk. 2).

ii) Siphon type rain recorder (Casella).

III.1.2.1 Standard Gauge

One standard raingauge (127mm. diameter) was installed with its rim 30.5cm. above the ground at the same location as the 152mm. gauges Nos. 1, 2 and 3 shown already in Figure 7. A view of that location can also be seen from Plate 2 where one of the homemade 152mm. gauges (No. 2) and the siphon rain recorder (Casella) are pictured together with the 127mm. standard gauge. The reason for the employment of this gauge was to provide data for comparing rainfall readings from different raingauge types. This gauge also served to check the accuracy of the calibration of the 152mm. gauges.

Rainfall measurements in the standard gauge were also made on a weekly basis on the same measurement days as 152mm. gauges. Rainwater caught in the gauge was measured directly as rain-depth in milimetres to the nearest 0.1mm. by the use of a calibrated measuring glass tube. The gauge was installed on 6 September 1977 and maintained throughout the experiment until 4 October 1978.

Plate 2 A view of Various Types of Raingauges Used to Measure Gross Precipitation outside Compartment 12 at Dalmeny Estate, near Edinburgh.

(1) Home-Made Plastic Funnel Gauge, 152mm. diameter.

(2) Siphon Rain Recorder (Casella), 203mm. diameter.

(3) Standard Raingauge (British Meteorological Office, MK 2), 127mm. diameter.

A comparison of the preliminary readings of the standard gauge with those of 152mm. funnel gauges revealed a close agreement. This can be seen from the figures provided in Table 10, where data for four weeks from 7 September to 10 October 1977 are shown.

III.1.2.2 Siphon Type Rain Recorder (Casella)

As was already been shown (Plate 2) one rain recorder (Casella) with a diameter of 203mm. was also installed at the same location as the standard raingauge. The rim of the rain recorder was 40cm. above the ground. Measurements with this gauge commenced on 8 June 1977 and continued throughout the experiment with only short interruptions due to frost. This particular raingauge provided very valuable information on the distribution of rainfall in time. Since it was not practical to make daily measurements of precipitation with the non-recording gauges mentioned above, the rain recorder was the only source from which detailed information about separate rainfall showers could be obtained. This information is of considerable value because of the important role of the distribution of rainfall in determining the interception loss which has already been mentioned.

Table 10 Comparison of the Preliminary Gross Precipitation Between a Standard Raingauge and Plastic Funnel Gauges at Dalmeny.

Period	Mean of Plastic Funnel Gauges(mm)	Standard Gauge(mm)
7-13 September 1977	20.0	18.2
21-29 September 1977	32.9	32.2
30-5 October 1977	20.2	17.4
6-10 October 1977	54.6	54.6

III.2 MEASUREMENT OF THROUGHFALL

III.2.1 Throughfall Measurement in the Scots Pine

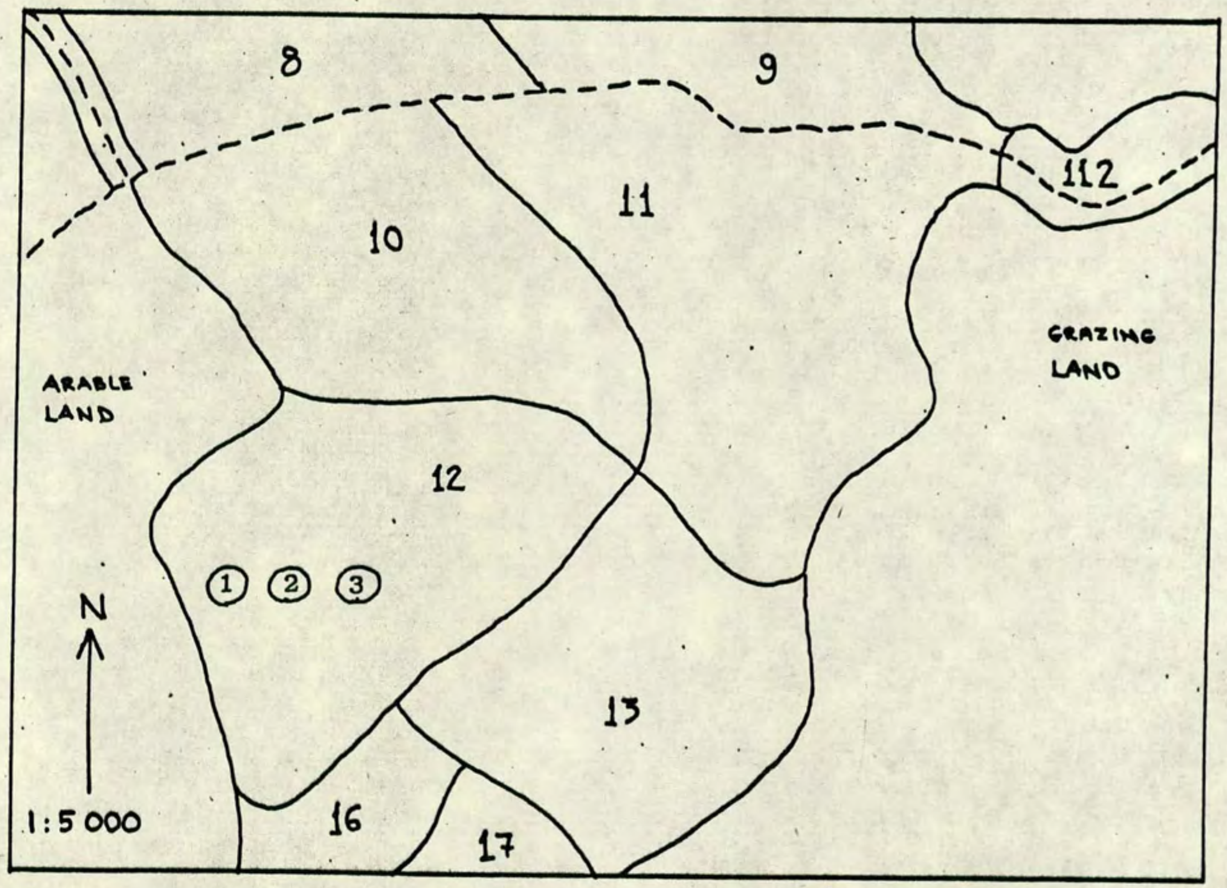
Throughfall observations in the Scots Pine experiment were made by means of 152mm. plastic funnel gauges identical to those used for determining gross precipitation and by means of a siphon rain recorder (Casella). The main problems that had to be resolved in this aspect of the work were:

i) How many gauges to use in order to obtain accurate throughfall data.

ii) Where to locate them.

After careful consideration of the nature of the Pine stand (Compartment 12) and of the logistics of making throughfall measurements over a lengthly time period, it was decided that the objectives of this part of the thesis could best be achieved by concentrating effort on three small plots; one on the edge of the forest and the other two in the inner part of the forest at about 50m. spacing. The exact locations of the plots are shown in Figure 10. Throughout the text, the plot on the forest edge will be referred to as Plot 1 and the others as Plots 2 and 3, respectively. Arranging the plots in a west to east direction seemed to offer the best prospects for detecting any edge effect that might occur because of the location of the pine stand with respect to the westerly winds that accompany most rain events in the area.

Figure 10 Map Showing the Locations of the Throughfall Sampling Plots in Pine in Compartment 12 at Dalmeny. Plot Nos: 1,2,3.



Initially, four gauges were installed on 6 May 1977 at random in each plot to check the calibration and the suitability of the gauge construction. At the same time, considerable attention was paid to the variations in the weekly throughfall amounts read from each gauge. To increase the sampling efficiency, the number of gauges per plot was increased to seven on 23 July 1977. Preliminary analysis showed that this sampling intensity, with a total of 21 gauges, was satisfactory for determining average throughfall within $\pm$10% accuracy limits (see Table 11). Therefore, this final layout was not altered until 3 August 1978. However, reliable information about the actual amount of variation in throughfall could only be acquired after more data had been collected. For this reason, the final analysis and discussion on the problem of the number of throughfall gauges is presented later. Note that a survey of literature (the results of which have already been shown in Table 2) also confirms that 21 gauges can be considered satisfactory.

The content of throughfall gauges was measured principally at weekly intervals on the same measurement days as for gross precipitation. The installation of the gauges was also identical to that of the gross precipitation gauges described. Measurements of throughfall were not made while rain fell. This was because rainfall would distort the data so that measurements from different gauge would not relate to the same amount of gross precipitation. Such distortion could be quite appreciable because it took several hours to deal with all the gauges used. For this reason, on the occasions when rain fell on a scheduled measurement day, that particular week's data was collected

Table 11 Results of The Preliminary Estimates of Number of Throughfall Gauges by Formula 4 for Pine at Dalmeny.

Weeks Ending	Average Throughfall(mm)	Standard Deviation(mm)	Error, 10% (mm)	Number of Gauges
29.6.1977	5.0	1.6	0.5	40
6.9.1977	39.6	8.4	4.0	17
29.9.1977	24.9	3.9	2.5	10
10.10.1977	43.8	6.4	4.4	9

at some later date. If the throughfall data was still distorted by an unforeseen rain shower, that data was added to that for the following week. By doing this, spoilt data was corrected and individual gauge readings were always for the same period of time.

Throughfall was measured regularly from 6 May 1977 to 3 August 1978 except for an interruption due to snow and frost lasting from 26 January to 1 March 1978.

It has already been mentioned that throughfall is often characterized by high spacial variation. This implies that throughfall gauge catch varies considerably from one gauge to another under the same type of forest canopy. Analysis of throughfall data obtained from the present experiment in the pine site showed that point throughfall readings had a distribution approaching very close to that of normal distribution (see also Figure 11 for frequency histograms). In such cases variation in throughfall can be expressed either as "range" or "standard deviation" (Snedecor & Cochran, 1967). The latter is preferred in this text because it has wide usage in the statistical tests, which are frequently used in the analysis of interception data.

Standard deviation was calculated (by APPLE Package Programme) for each weekly set of throughfall data and plotted against the arithmetic mean value of the corresponding gross precipitation readings in 152mm. funnel gauges. The resultant graph is given in Figure 12. A similar relationship was also established between standard deviation and mean throughfall, which was best represented by a semilogarithmic

Figure 11 Frequency Histograms of Throughfall Readings in Scots Pine.

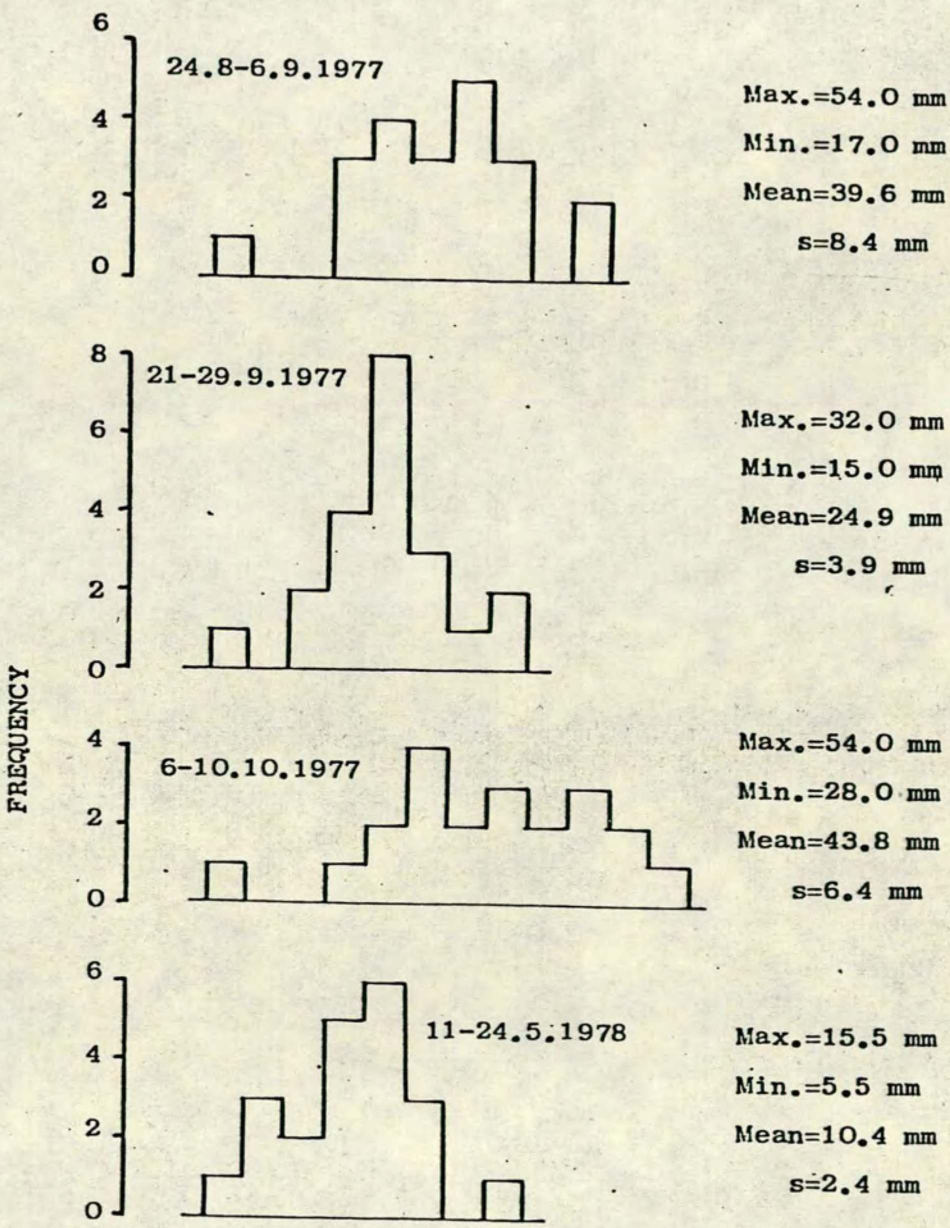
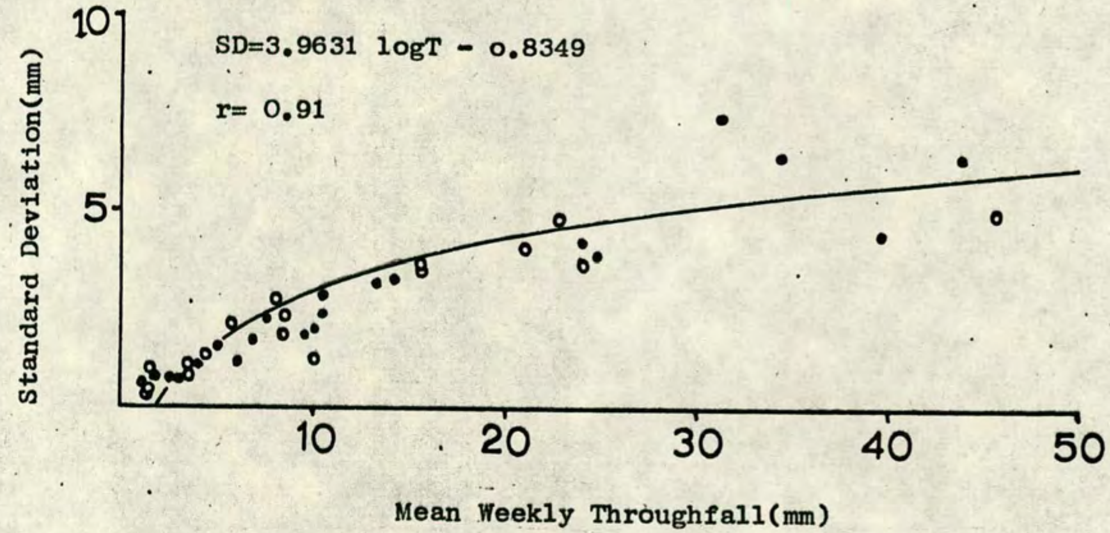


Figure 12 The Scatter Diagram of Standard Deviation of Mean Throughfall in Pine. Summer(•), Winter(o).

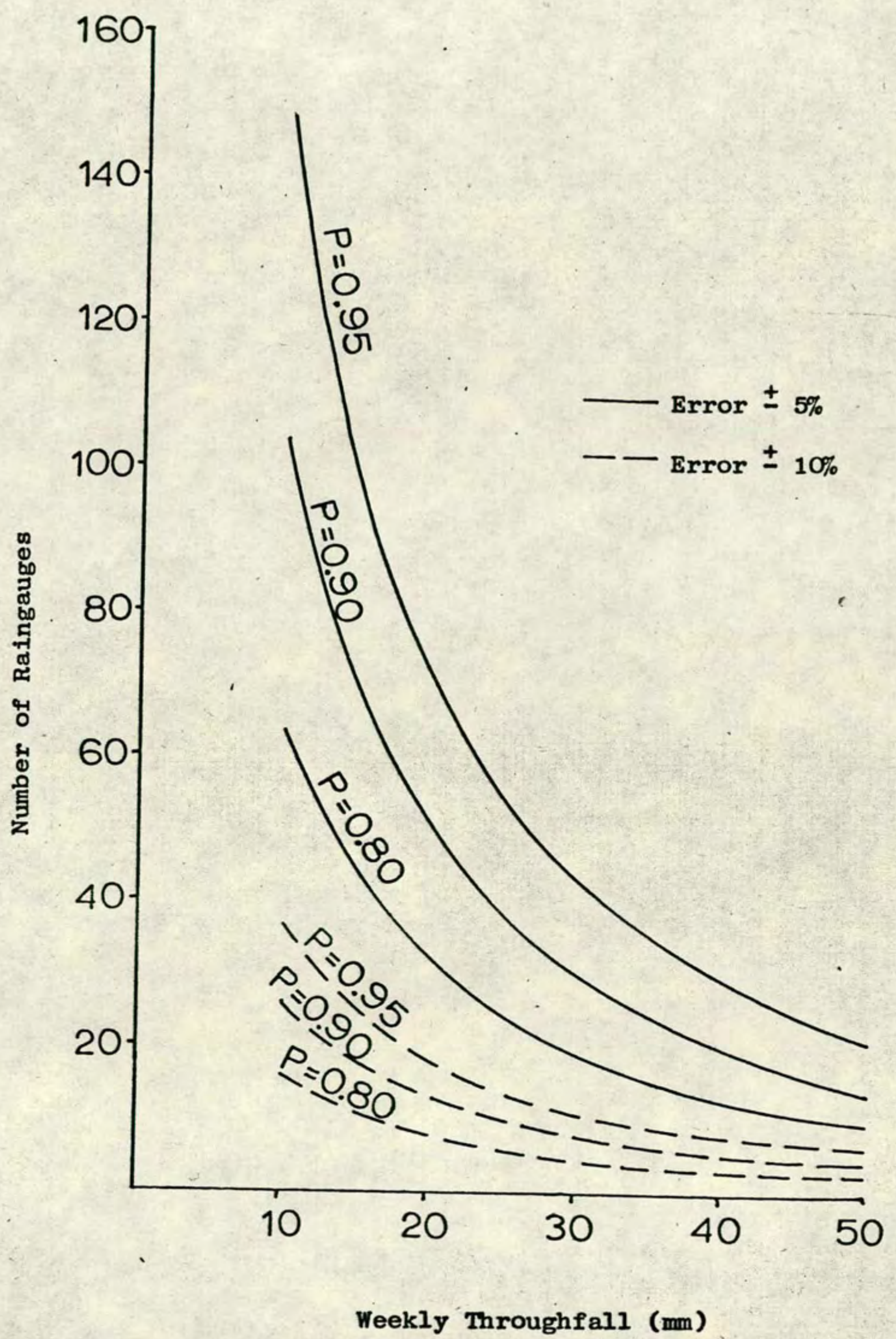


55.2

regression equation similar to that for the gross precipitation data shown already. Coefficient of variation was studied. However, it did not show as much affiliation as standard deviation and is, therefore not given here.

By utilizing the regression equation in Figure 12 $S = 3.9631 \log T - 0.8349$ and Formula 4, the number of throughfall gauges required for various accuracy and probability levels could be calculated. The results are shown in Figure 13 in the same way as those for gross precipitation (Figure 9). It is clear from Figure 13 that it requires a large number of gauges to measure small throughfall amounts ($<$20mm.) accurately. However, these numbers sharply decrease with increasing throughfall amount to as small a number as about 20 gauges for 50mm. rainfall per week to assure $\pm$5% accuracy limits at 95% confidence. It is also clearly shown in Figure 13 that if $\pm$10% error was tolerated in determining throughfall, a much smaller number of gauges becomes satisfactory. Since most of the annual precipitation in the area is accounted for by large rainfall amounts (per week) despite a large number of smaller rain events a greater error can be tolerated for the latter ones. Therefore, it was concluded that the present gauging intensity (total 21) was reasonably satisfactory. However, a greater number of gauges would naturally have yielded more satisfactory results.

Figure 13 Numbers of Throughfall Gauges Estimated by Formula 4 for Pine at Dalmeny.



III.2.2 Measurement of Throughfall in Deciduous Species

III.2.2.1 Mature Beech (Be 1)

Throughfall sampling in the mature Beech stand of Compartment 12 (denoted by Be 1) was initiated on 26 May 1977 with the installation of eight plastic funnel gauges (152mm.). This number was later increased to 11 from 21 December 1977 onwards. A continuous record of throughfall was collected until 4 October 1978, except for the frost period that has already been alluded to. The gauges were installed in the same manner as for the pine. The locations were chosen randomly at various distances from the tree bases in order to sample all variation in throughfall. Measurements were made at one-weekly intervals as usual on the same days as for the Pine.

Analysis of the data indicated a certain pattern of the distribution of throughfall under the mature Beech. Gauge readings for three typical weekly periods and some basic statistical analyses are given in Table 12. It is obvious from this table that abnormally high standard deviation occurred (over 100% C.V.). This is due almost entirely to the readings from gauge No. 7 which always measured freakishly high throughfall amounts. On several occasion, the site was visited during a prolonged rainfall in order to make personal observations of this situation. It was observed that gauge No. 7 was receiving large water drops falling frequently from a main tree limb under which the gauge happened to be installed. However, it was still difficult to estimate how many such dripping points occurred in a unit area under the mature Beech canopy.

Table 12 A Selection of The Typical Throughfall Data for Mature Beech(Be1), Dalmeny. All in mm.

Gauge No	19-26 July 1977	30Sep-5 Oct 1977	4-10 May 1977
1	4.0	14.0	7.6
2	4.0	16.0	4.9
3	4.5	12.0	3.9
4	3.0	12.0	5.6
5	4.0	9.0	4.0
6	4.5	11.0	4.6
7	21.0	40.0	44.0
8	5.0	12.0	5.3
9	-	-	4.4
10	-	-	3.8
11	-	-	4.5
Minimum	3.0	9.0	3.8
Maximum	21.0	40.0	44.0
Mean	6.3	15.8	8.4
Standard Deviation	6.0	10.0	11.8
Coefficient of Variation	96%	64%	141%

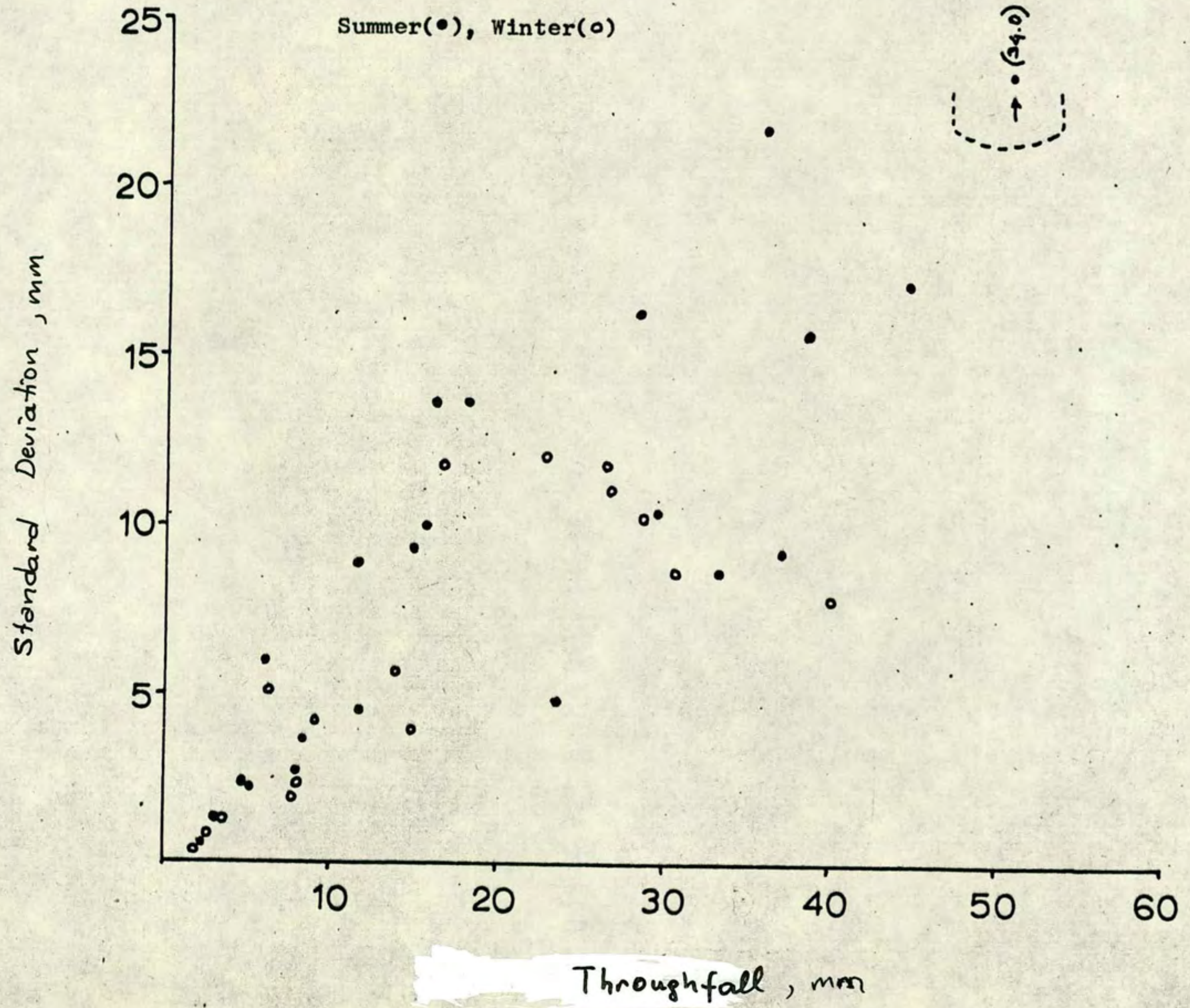
It can also be seen from Table 12 that throughfall variation was so high that the addition of three more gauges did not contribute towards improvement of the sampling efficiency. This implied that, in order to achieve better estimates of throughfall under mature Beech, a highly intensive sampling density was necessary. It was also clear that special attention should be paid to dealing with the dripping points under limbs. For example, it was estimated that, from the available information for the period 4 May to 10 May 1977 (see Table 12), 637 gauges were necessary according to Formula 4 to determine throughfall with ±10% error at 95% probability. Unfortunately, it was not possible to use such effective sampling described above in the time available.

The scatter diagram of standard deviation plotted against throughfall is given in Figure 14. Since the high variability of throughfall led to inaccurate estimates of mean weekly throughfall under the mature Beech canopy, it was regretfully decided not to analyse this data further nor to compare it with data collected in other stand types such as the Pine.

III.2.2.2 Young Sycamore (S 2)

Throughfall was also measured under young Sycamore trees in Compartment 13, i.e. plot Sycamore (2), by means of 11 funnel gauges (152mm.). The location of the gauges was determined randomly by drawing numbers representing the coordinates of a one metre grid that

Figure 14 The Scatter Diagram of Standard Deviation of Mean Throughfall in Old Beech.



had been established on the ground beforehand. The installation, maintenance and reading of the gauges were carried out in the same way as described already for other sites.

Data gathered from the experiment on this plot consisted of 38 sets of weekly throughfall readings from 23 June 1977 to 4 October 1978. The standard deviation of each set was calculated and the results were plotted against the arithmetic mean throughfall in the same way as for Pine and mature Beech. The results are given in Figure 15. Standard deviation shows wide scatter, some of which is apparently due to the seasonal changes in the forest canopy causing the variation to decrease during leafless period. However, a great deal of the scattering must be attributed to various weather conditions that prevailed during precipitation hours. In an attempt to detect the effect of seasonality on the level of standard deviation of throughfall, the summer (May to October) and winter (November to April) data was grouped and regression analysis was applied to the two groups separately. However, this did not improve the curve fitting to any great extent and the data was treated as a whole regardless of seasons for further interpretation. It was found that a semilogarithmic regression equation fitted the scatter diagram best, and this is shown in Figure 15.

The numbers of gauges required for 5% and 10% error limits at three different probabilities (95%, 90% and 80%) were calculated according to Formula 4; the results of which are depicted in Figure 16 in the same fashion as for Figures 9 and 13. Figure 16 shows similarly that the present sampling density with 11 gauges was sufficient to measure

Figure 15 The Scatter Diagram of Standard Deviation of Mean Throughfall in Sycamore in Compartment 13, Dalmeny.

Summer(•), Winter(○)

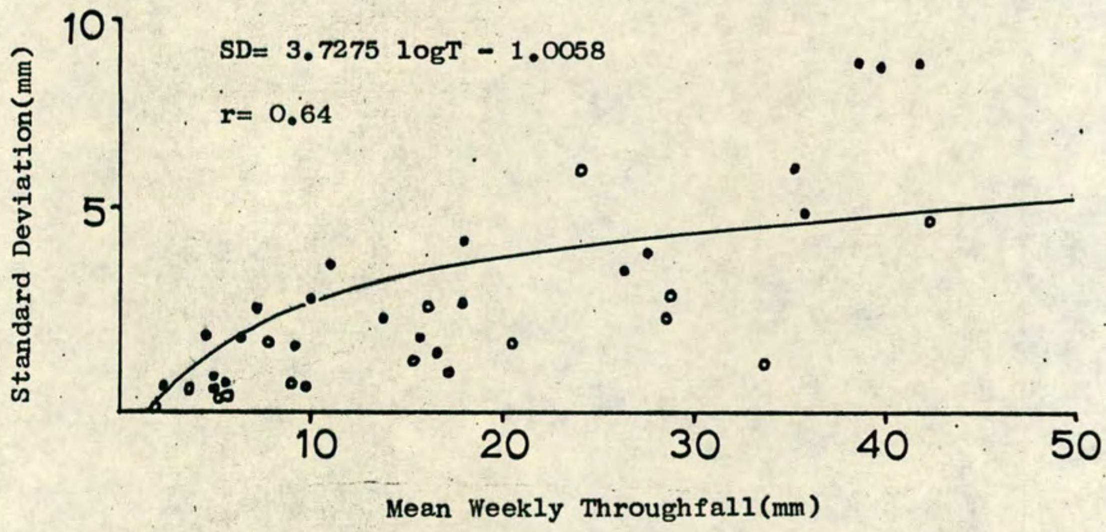
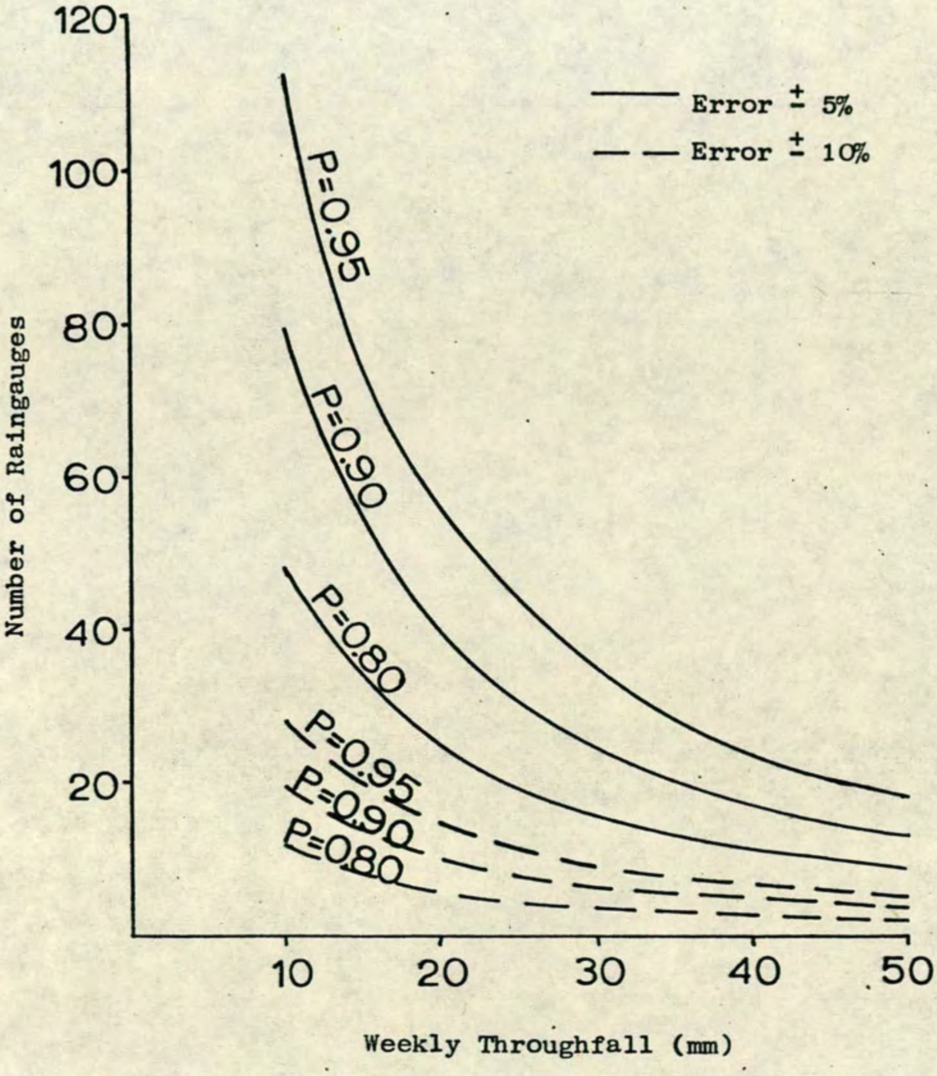


Figure 16 Numbers of Throughfall Gauges Estimated by Formula 4 for Sycamore in Compartment 13 at Dalmeny.



throughfall accurately with $\pm10\%$ of the mean weekly throughfall at high probability levels. However, determination with $\pm5\%$ error limits would have required large numbers of gauges: 55 gauges, for example, being needed to measure 20mm. throughfall with 5% error at 95% probability.

III.2.2.3 Adjacent Plots of Young Beech (Be 2) and Sycamore (S 1)

Interception was also studied in two adjacent young plantations of Beech and Sycamore in Compartment 11. Measurements of throughfall in both sites were initiated on 26 May 1977. To begin with, seven and six funnel gauges (152mm.) were installed at random in Be(2) and S(1), respectively, and two weeks later (8 June 1977) these numbers were increased to 12 and 13, respectively.

Apart from the sampling and instrumentation described above, other instrumentation and sampling techniques were also employed in the two sites in an attempt to compare various gauge types and sampling intensities.

In the Sycamore plot, for example, the 13 plastic funnel gauges mentioned above were abandoned on 30 June 1977 and a grid with 0.5m. spacing was established under a single Sycamore tree, which was selected as typical of the trees at that particular plantation. 23 plastic funnel gauges (152mm.) were installed in the grid and a continuous record was gathered for the period from 30 June 1977 to 4 October 1978. The layout of the gauges in the 0.5m. grid is shown in Plate 3 . This approach was used for three purposes:

Plate 3 A view of Throughfall Gauges Installed in a 0.5m. Grid under a Sycamore Tree in Compartment 11, Dalmeny.

i) To increase the sampling efficiency.

ii) To study the pattern of distribution of throughfall in relation to distance from the tree base.

iii) To study the effect of spacing between gauges in improving throughfall sampling.

Analysis of the weekly throughfall data obtained from the grid sampling showed that there was no pertinent relationship between the point throughfall amount and the distance from the tree base. Figure 17 shows that throughfall during a typical week was unevenly distributed under the sample tree with no affiliation to gauge position relative to the tree base. It should also be pointed out that the throughfall pattern appeared to be entirely random, so that individual gauge catches were not persistently greater or smaller than the average nor relative to any other gauge. However, there was one exception. That was gauge No. 16 which always caught the largest amount of throughfall water because of its location under a dripping point from a branch overhead.

It was also considered that a 0.5m. grid did not reveal any affiliation between gauge catch and its distance from the tree base probably not because such a relationship had not existed but because the spacing of 0.5m. was too great to show the real throughfall pattern. For this reason, an attempt was made to install some plastic funnel gauges under another Sycamore tree not far away from the grid at much smaller spacing than 0.5m. But this was not possible because the gauges had to be buried into the ground by some 10cm. whereas the root system of the trees did not allow such installation. There was another difficulty which would have been faced: namely that the gauges would

Figure 17 The Distribution of Throughfall under a Tree of Sycamore for 26 Oct-1 Nov. 1977. Data from 0.5 metre Grid. All in mm.
(Figures in brackets indicate gauge numbers)

		44.0 (1)		
45.0 (2)	42.0 (3)	45.0 (4)	40.0 (5)	48.0 (6)
40.0 (7)	40.0 (8)	42.0 (9) TREE BASE	40.5 (10)	42.0 (11)
41.0 (12)	39.0 (13)	34.0 (14)	35.0 (15)	50.0 (16)
41.0 (17)	48.0 (18)	43.0 (19)	49.0 (20)	36.0 (21)
		41.0 (22)	44.0 (23)	

Maximum=50.0mm. Minimum=34.0mm. Mean=42.2mm.

Standard Deviation=4.2mm. Coefficient of Variation=9.9%

have been so close to each other that it would have been difficult to gain access to them to make the necessary measurements. These obstacles were overcome by constructing a large perspex trough which housed 21 plastic funnel gauges. The trough is illustrated in Plate 4. The following paragraph is concerned with the design of the trough and throughfall sampling with it.

The trough was built out of 5mm. thick perspex sheet in the form of a 60° triangle with each side being 104cm. The dimensions were estimated in such a way that 21 152mm. plastic funnel gauges could be housed. The trough was rested on a triangular dexion frame which had three legs. When the gauges were put in the trough there were small gaps between them. Throughfall naturally also fell through these gaps and this water was collected by the trough and led into a plastic container by means of a piece of rubber hose attached to the trough at one corner. This throughfall water was separately measured and converted to water equivalent depth on the basis of the area of the inter-gauge gaps which was in turn estimated as the total receiving area of the trough minus the total area of the 21 plastic funnel gauges. To ensure that water drained from the trough into the storage container, the device was installed with a slight slope.

The trough was set up under a Sycamore tree with one of its corners towards the tree bole. Throughfall was measured weekly both in the 21 gauges and in the trough itself. After each weekly measurement, the trough was moved around the tree by 60° in order to take all of the throughfall variation into account. Data collected by

Plate 4 The Construction and Installation of the Triangle Perspex Trough housing 21 Plastic Funnel Gauges.
Site: Sycamore(S1) in Compartment 11, Dalmeny.

this method span the period from 30 September 1977 to 25 January 1978.

Analysis of the data collected during this period showed only small differences between the mean of the 21 gauges and the amount measured from the trough. The difference was 2.1mm. at most and usually less than 1.0mm. This is attributable to evaporation from the trough and to the rainwater that was needed to wet the external surface of the 21 gauges and the inside of the trough.

In Figure 18 the data collected from the trough and the gauges are given for the same period as the grid data displayed in Figure 17. The same conclusion is reached that throughfall is not dependent on the distance from the tree.

Further statistical analysis was applied in order to test as to whether average throughfall values obtained from the 0.5m. grid and the trough differed significantly. The statistical methods of F-test and t-test are readily available for such purposes (Snedecor and Cochran, 1967). The results of the F-test and the t-test are shown in Table 13 and Table 14 respectively. It can be seen from the latter that average weekly throughfall differed significantly at 95% probability level only on four out of 12 occasions. The interpretation of this is therefore that the sampling technique of installing the gauges very closely, literally touching each other as in the case of the trough, does not have any superiority over the sampling with a 0.5m. grid. This conclusion is justified because both samplings were carried out under similar canopy conditions and with similar sample sizes, 21 and 23 gauges, for the same period and gross precipitation pattern and amounts.

<u>Figure 18</u> The Distribution of Throughfall under a Tree of Sycamore During 26 Oct.-1 Nov.1977. Data from the Gauges housed in the Triangle Trough. All in mm.

TREE BASE

38.0

40.0 45.0

45.0 45.0 43.0

43.0 43.5 40.0 42.0

41.0 43.5 39.0 35.0 37.0

42.0 44.0 41.0 38.0 33.0 36.0

Maximum=45mm. Minimum=33.0 Mean=40.7

Standard Deviation=3.5mm. Coefficient of Variation=8.6%

Table 13 The Results of F-Test applied to 0.5m Grid and the Trough Data

Period	f_1	f_2	F	P	
30.9.1977 - 5.10.1977	22	20	1.08	0.50	
6.10.1977 - 10.10.1977	20	22	1.53	0.20 - 0.50	
19.10.1977 - 25.10.1977	22	20	1.00	0.50	
26.10.1977 - 1.11.1977	22	20	1.44	0.20 - 0.50	
2.11.1977 - 8.11.1977	22	20	3.41	0.01	*
9.11.1977 - 15.11.1977	22	20	4.00	0.01	*
16.11.1977 - 22.11.1977	22	20	22.35	0.01	*
23.11.1977 - 6.12.1977	22	20	27.04	0.01	*
7.12.1977 - 13.12.1977	22	20	2.64	0.01 - 0.05	*
22.12.1977 - 30.12.1977	22	20	113.78	0.01	*
31.12.1977 - 25.1.1978	22	20	12.04	0.01	*
9.3.1978 - 17.3.1978	22	20	268.96	0.01	*

* Variances can be assumed not to be equal at 95% probability

Table 14 The Results of T-Test applied to Throughfall Data obtained from the Trough and 0.5m Grid

Period	$\bar{x}_1 - \bar{x}_2$	d.f.	t	P	
30.9.1977 - 5.10.1977	3.7	42	4.51	<0.001	*
6.10.1977 - 10.10.1977	1.0	42	0.58	>0.50	
19.10.1977 - 25.10.1977	0.6	42	4.00	<0.001	*
26.10.1977 - 1.11.1977	1.5	42	1.29	0.20 - 0.40	
2.11.1977 - 8.11.1977	2.0	33	3.51	0.001 - 0.005	*
9.11.1977 - 15.11.1977	0.3	33	0.42	>0.50	
16.11.1977 - 22.11.1977	0.3	24	0.27	>0.50	
23.11.1977 - 6.12.1977	0.7	23	1.28	0.20 - 0.40	
7.12.1977 - 13.12.1977	1.3	37	4.11	<0.001	*
22.12.1977 - 30.12.1977	1.6	22	1.19	0.20 - 0.40	
31.12.1977 - 25.1.1978	1.7	26	1.32	0.10 - 0.20	
9.3.1978 - 17.3.1978	1.1	22	0.64	>0.50	

* Significant at 95% probability

In Figure 19 the scatter diagram of standard deviation plotted against average weekly throughfall is shown. In the calculation of standard deviation of all data collected from the 13 randomly located gauges (152mm.), the 0.5m. grid, and from the trough were combined to achieve better estimates. A semilogarithmic regression equation calculated is also given in Figure 19. Similarly the number of gauges calculated by Formula 4 are shown in Figure 20. Since as many as 44 plastic funnel gauges (152mm.) were used at one time for part of the experiment in young Sycamore in Compartment 11, it can be inferred from Figure 20 that the sample size used was large enough for accurate estimates within small error limits at high probability levels.

As has already been mentioned, throughfall sampling in young Beech in Compartment 11 was commenced at the same time as the neighbouring Sycamore site by installing 12 gauges at random. A continuous record was collected until 30 September 1977. These gauges were then abandoned because they had to be moved to the Sycamore site in the vicinity, where they were needed for the triangle perspex trough. Measurement of throughfall under young Beech trees was later resumed with the use of the trough. The trough was shifted from the Sycamore on 17 March 1978 and remained at the young Beech site until 4 October 1978 when the throughfall sampling in all locations was brought to an end.

The results of analysis concerning the variation in terms of standard deviation are shown in Figure 21. In this figure, data collected from both random gauges and the trough are presented. It is clear from this figure that the standard deviation of throughfall

Figure 19 The Scatter Diagram of Standard Deviation of Mean Throughfall in Sycamore in Compartment 11, Dalmeny. Summer(•), Winter(o).

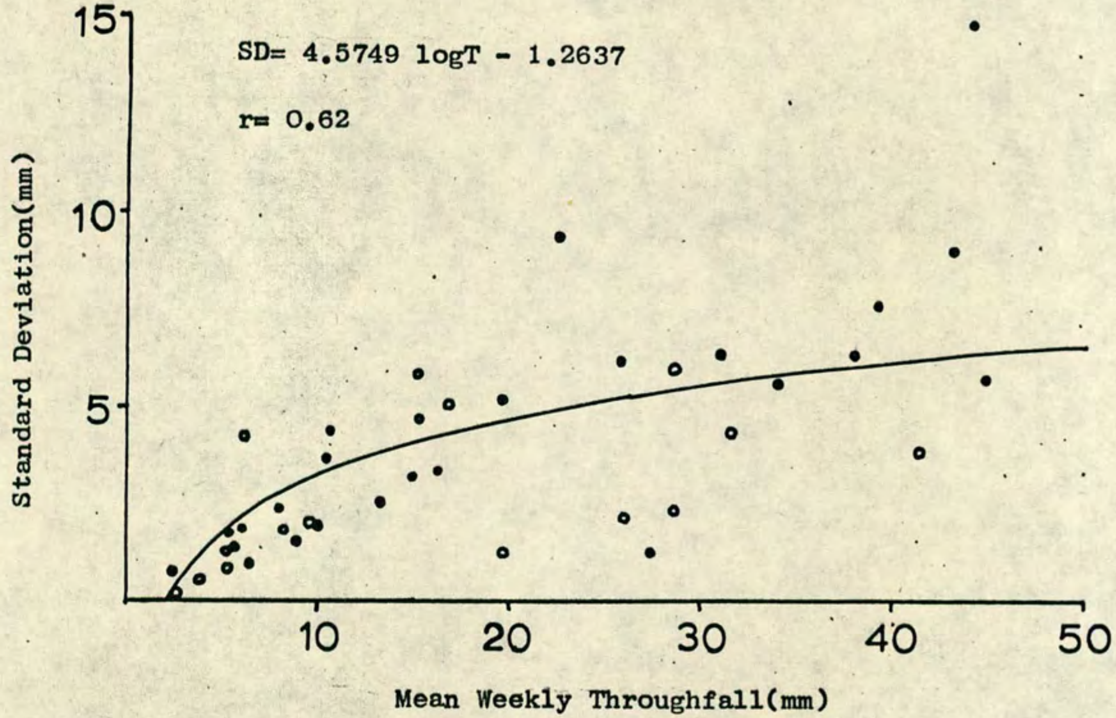


Figure 20 Numbers of Throughfall Gauges Estimated by Formula 4 for Sycamore in Compartment 11 at Dalmeny.

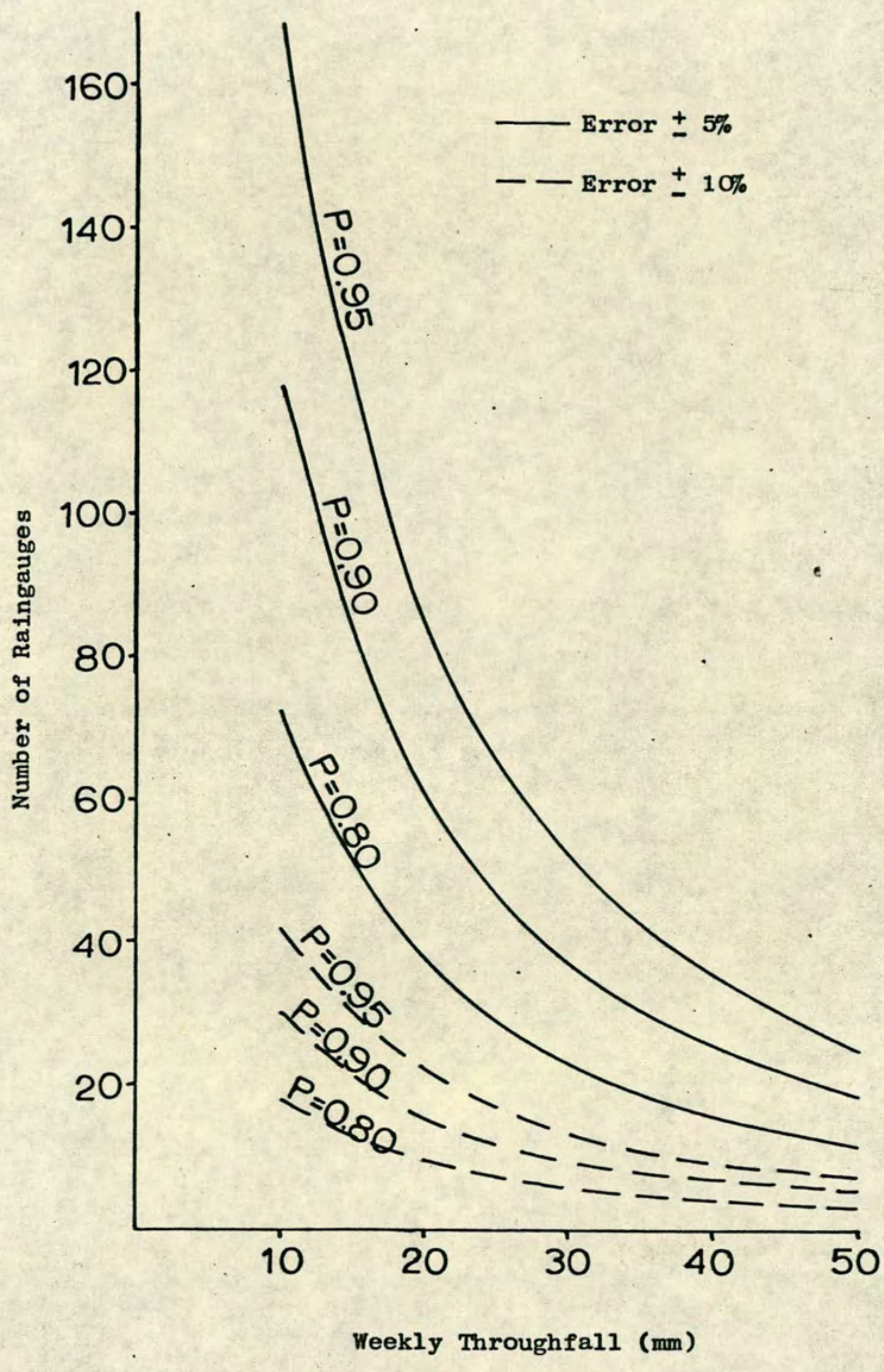
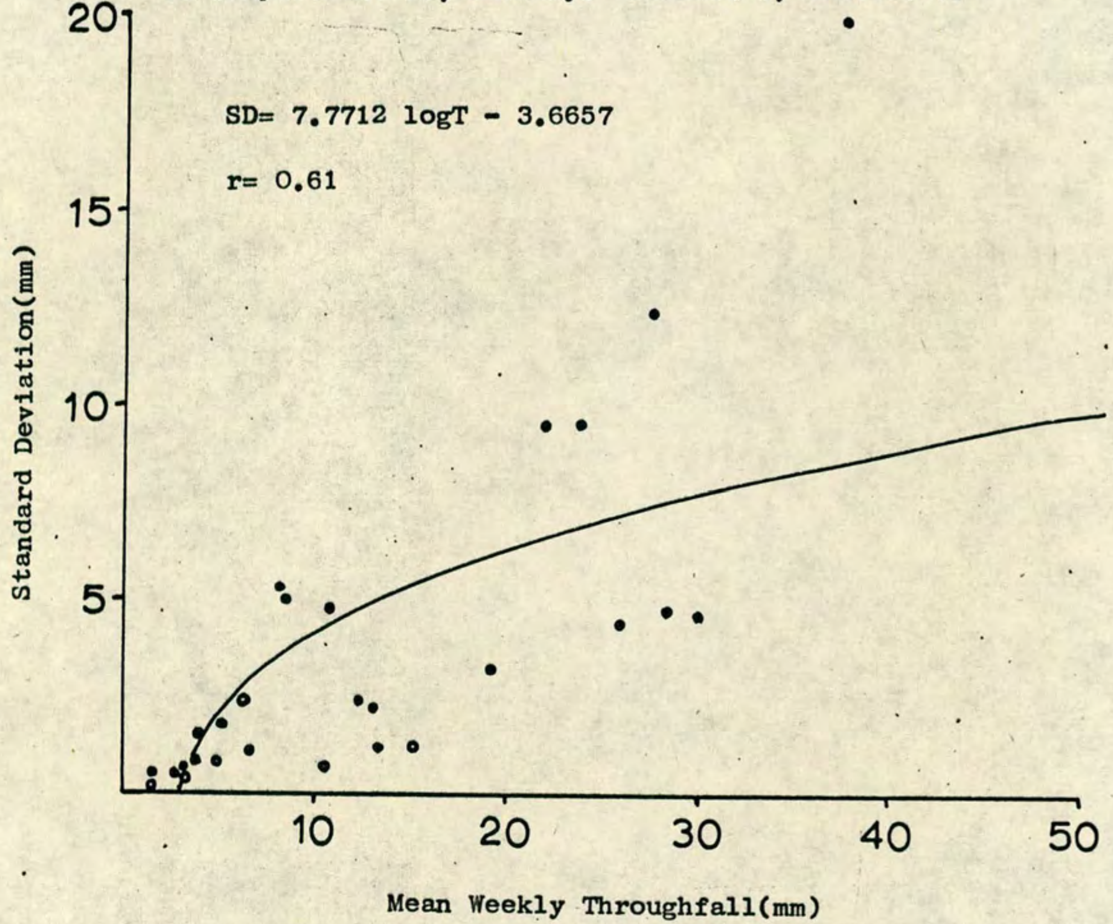


Figure 21 The Scatter Diagram of Standard Deviation of Mean Throughfall in Young Beech in Compartment 11, Dalmeny. Summer(•), Winter(o).



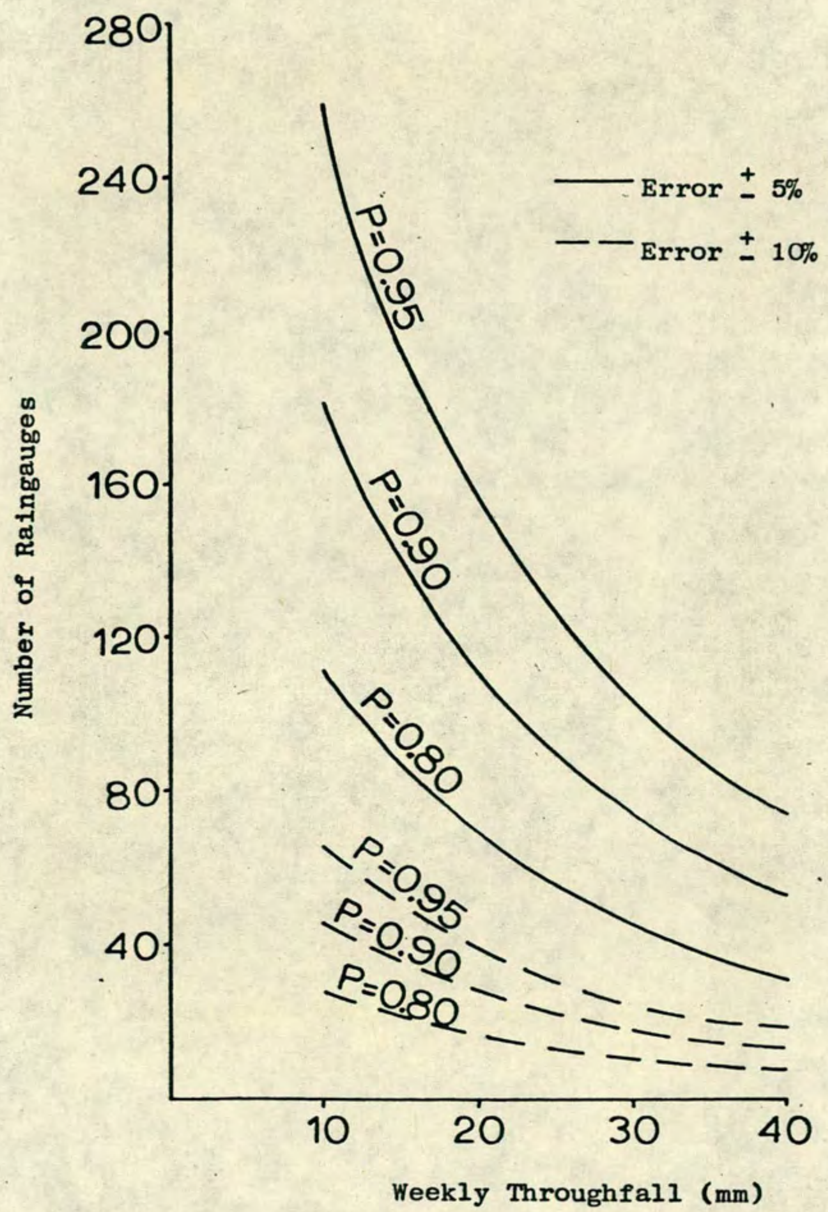
under young Beech is higher than the other experimental plots except for the mature Beech in Compartment 12. As a result of this, the estimates of the number of gauges needed to achieve readings giving only 5% and 10% error of the mean throughfall at 95%, 90% and 80% probability levels are quite large. Nevertheless, Figure 22 suggests that the present sample size of up to 21 gauges was sufficient for the measurement of throughfall with an error of 10%.

III.2.3 Experiments with Tipping-Bucket Gauges

Work described so far provided only weekly data. It was only natural that an average weekly gross precipitation or throughfall value comprised several rain events that occured during each week. This in turn did not indicate how precipitation was distributed by forest canopies during each separate rain event. It was therefore desirable to collect data in such a way so that separated showers could be recorded. An opportunity to do this arose in August 1978 when several tipping-bucket mechanisms and an event recorder became available.

In addition to the weekly samplings with 152mm. plastic funnel gauges, four Artech tipping-bucket gauges were also used to measure both gross precipitation and throughfall. The gauges were connected by cable to a Rustrak event recorder so that it was possible to collect a detailed record of gross precipitation and throughfall automatically registered by the event counter against time.

Figure 22 Numbers of Throughfall Gauges Estimated by Formula 4 for Young Beech in Compartment 11 at Dalmeny.



As shown in Plate 5 sampling of gross precipitation and throughfall was achieved by means of three and six plastic funnels (152mm.) respectively. The funnels were installed at a height of about 0.6m. on top of wooden poles. The water caught in the funnels was led to the tipping-bucket mechanism through a length of 5mm. plastic tube. By connecting more than one funnel to a single tipping bucket, the total receiving area and therefore the sampling efficiency was increased. The tipping bucket was housed in a portable wooden box (black in colour). The design of the tipping-bucket device and recording system can also be seen from Plate 6. As the bucket was filled with rainwater, it became unbalanced and tipped over generating small electrical current which was in turn registered on the chart of the Rustrak recorder as one event. The tipping buckets were calibrated so that the water depth represented by one event could be calculated. A specimen of the event recorder chart is displayed in Figure 23. Channel 1 was allocated to gross precipitation. Throughfall was recorded on channels 2, 3 and 4. Although the chart was run at a constant speed of one inch per hour, the time was also recorded at one minute intervals on channel 5 by means of a timer integrated circuit. The power for the operation of the whole system was supplied by a 12 Volt car battery. The use of the timer eliminated any inprecision in time running due to the weakening of the power supply. However, this was not vital because it was observed that a sound car battery could last at least three months with no reduction in chart speed.

As for the sampling of throughfall, three pieces of equipment were installed on Plot 2 in the Pine stand on 3 August 1978. A record

Plate 5 Design and Installation of Tipping-Bucket Gauges.

(A) Measurement of Gross Precipitation outside Pine.

(1) Plastic Funnels(152mm. diameter)

(2) Wooden Box Housing a Tipping Bucket Device

(3) Casella Rain Recorder(203mm. diameter)

(4) Standard Raingauge(127mm. diameter)

(A)

Plate 5

(B) Measurement of Throughfall Under Pine in Compartment 12, Dalmeny.

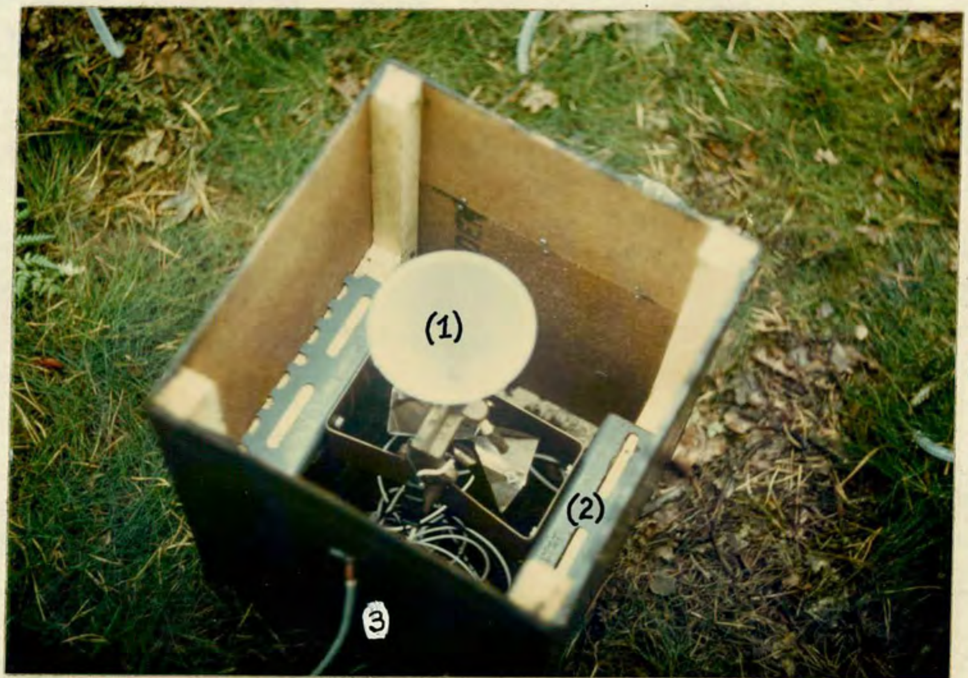
(1) Stevenson Screen housing the Rustrak Event Recorder.

(B)

Plate 6 Detailed Views of The Tipping-Bucket and Recording Devices.

(A) Tipping-Bucket Mechanism. (1) Collecting Funnel, (2) Tipping Device, (3) Cable to the Recorder.

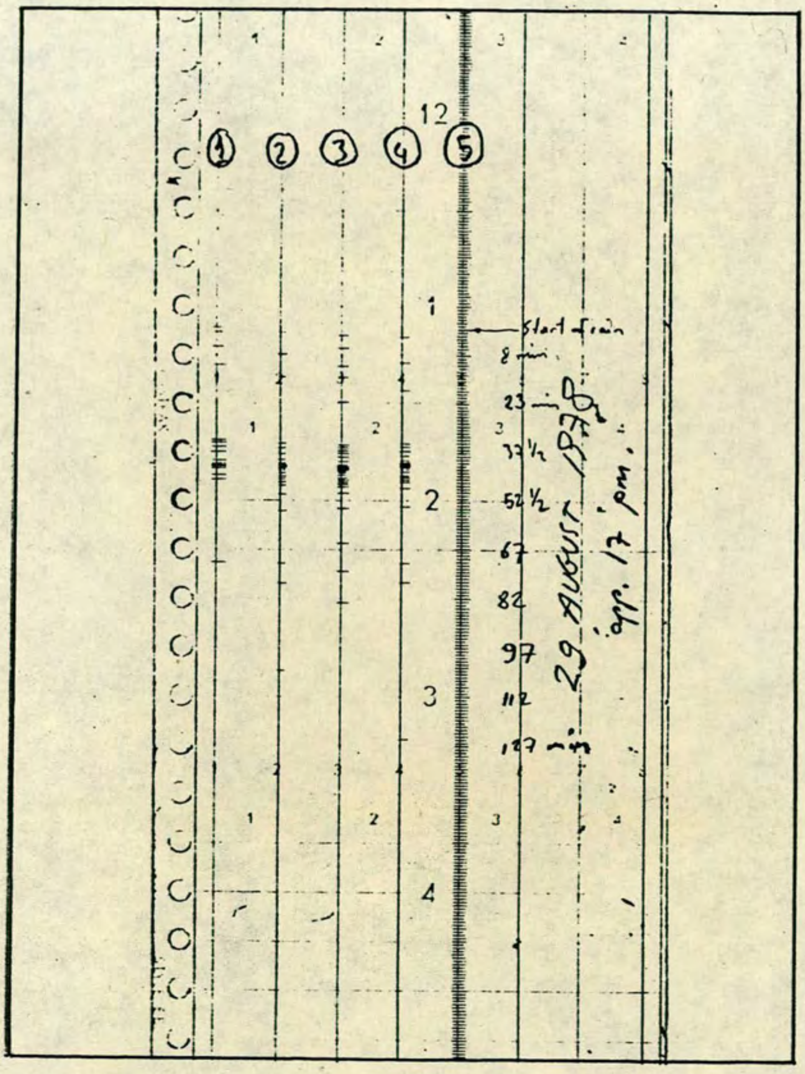
(B) Recording System. (1) Rustrak Event Recorder, (2) Battery(12V).



(A)

(B)

Figure 23 An Example of the Rustrak Event Recorder's Chart. Channel 1 was allocated to Gross Precipitation, Channels 2, 3, 4 to Throughfall and Channel 5 to Time.



of both throughfall and gross precipitation falling outside the stand was collected until 12 September 1978. Unfortunately, this record is not continuous because:

i) The plastic tubes leading water from the funnels to the tipping-bucket devices frequently became blocked with pine needles.

ii) Trouble was encountered with the recording system.

Nevertheless some useful data was collected.

The gauges were later moved from the Pine stand on 12 September 1978 and two sets with 12 funnels were installed in the young Sycamore plantation in Compartment 11, and another set was established in the adjacent young Beech. A gauge was also installed in a small forest clearance some 30m. away from the others. Throughfall and gross precipitation data was collected from these sites until 2 November 1978, when the field work as a whole was ended.

III.3 MEASUREMENT OF STEMFLOW

It has already been mentioned that many types of collars have been used to collect stemflow. Two types seemed particularly suitable for work at Dalmeny. These were polyurethane foam collars, and Mastik strip ones. To decide which was the better, preliminary experiments were carried out on trees located on the University campus in Edinburgh.

III.3.1 Polyurethane Foam Collars

Likens and Eaton (1970) described this type of collar which is made out of polyurethane foam. This material is light, solid and water-tight. The foam is obtained by mixing two liquid components in appropriate proportions, generally 1:1. These components are polyol composition and isocyanate. When the two components are mixed and stirred, a foaming action starts. As soon as foaming is observed, the liquid is poured into a polyethylene mould attached beforehand around the tree trunk. As the foaming action continues, the foam expands and fills the mould. Since the foam does not stick to the mould, it is easily removed and the foam collar remains on the tree. The sealing between foam and tree bark is perfect. A trough is carved in the top of the collar with a knife. Stemflow water is led to a container by means of plastic tube attached to the polyurethane collar.

A collar was installed on a deciduous tree on the University campus (Plate 7 a) and its performance was found to be satisfactory.

Plate 7 Stemflow Gauges on The University Campus, Edinburgh.

(1) Polyurthane Foam

(2) Expanded Mastik Strip.

(1)

(2)

However, it has certain disadvantages. For example, the liquid components are costly and it requires a long time to construct one collar - approximately three hours in the workshop and probably longer in field conditions. Although the foam is absolutely water-tight and a good sealer, it is inflexible and breakable; therefore it might not withstand the radial expansion due to tree growth. However, this was not tested because of the time limitation.

III.3.2 Expanded Mastik Strip Gauges

Another stemflow collar was built and tested. This one was identical to those which were being used in an experiment conducted in the Rivox Forest in the spring of 1977 by the Institute of Terrestrial Ecology; the results of which have later been published by Ford and Deans (1978). This gauge cost less than the foam one and is more easily installed. One such collar was tested on the campus (Plate 7 b) and as its performance was found to be entirely satisfactory, it was decided to use this device at Dalmeny in preference to the other.

All stemflow collars were installed on the two dry days, 16 and 17 June 1977, because the surface of the tree bark had to be dry in order to achieve satisfactory sealing. The collars were attached to the trees at about 0.7m. height above the ground. Firstly, some preparation had to be made in order to ensure a clean and smooth surface. This did not require much work in the case of deciduous trees since they have smooth bark. As can be seen from Plate 8 , the bark of Pine trees on the

Plate 8 View of an Expanded Mastic Strip Stemflow Gauge Installed on Pine, Dalmeny.

(1) Expanded Mastic Strip(50mm. wide)

(2) Clout Nail(20mm.)

(3) Plastic Tube(5mm. diameter)

(4) Plastic Container(30 Litre)

other hand had to be smoothed with a knife. Dust on the sample tree was also brushed off. On the mature Beech trees collars could only be put at higher elevations because the trunk diameter was often very great (over 60cm.) and the horizontal sections at 0.7m. above the ground were often very irregular.

When the preparation of bark was completed, an adequate length of expanded mastik strip, 3mm. thick and 50mm. wide, was cut so that it would surround the circumference and also overlap by about 10cm. To seal the strip, a special putty-like material called expandite secomastik was used. This sealer, khaki in colour, was applied to the previously cut mastik strip along a line by means of a mastik gun. A piece of plastic tube, with an internal diameter of 5mm., was also put across the mastik strip at some point in the middle and was sealed with secomastik. Finally, the mastik strip and the plastic tube were sealed to the trunk. The plastic tube was pulled down to the extent where the top end was at the same level with the sealer between the trunk andthe mastik strip. This plastic tube was used to convey stemflow water into a plastic container of about 30 litres volume. The mastik strip projected about 10mm. from the trunk. This gap was considered enough to allow stemflow water to flow freely in the gutter without overflowing; but not so large that significant amounts of rain would fall directly into it. No overflowing was observed even during the heaviest rain showers. The collars on young Beech and Sycamore trees were secured with wire whereas on Pine and mature Beech treesclout nails ($^3/4$ inch) were used, because wire failed due to the regular surface and large diameter of the trees. The clout nails used were small enough not to do any harm to the sample trees.

III.3.3 Selection of Stemflow Sample Plots

Stemflow was measured on nine small plots located in the same areas used for throughfall measurement. The plots are shown in Figure 10. Each plot enclosed five contiguous trees. When selecting the plots, care was taken to ensure that the trees in them were representative of that particular stand type in terms of tree diameter, height and canopy structure. Where more than one plot was chosen on a single site, the plots were located according to the exposure to wind. As shown in Figure 10 , for example, three plots were taken in the Pine site, one of which (No. 1) was on the west margin of Compartment 12 and the other two plots were chosen at some 50mm. spacing at the same locations as for throughfall. In each of the plantations of Sycamore (S 1) and Beech (Be 2) in Compartment 11, two plots were used; one being on the east edge and the other at 15m. distance in the inner part of the plantation. By taking more than one plot in a single forest type, it was intended not only to increase the sampling efficiency but also to detect any variation in stemflow due to the edge effect.

In view of the comments made earlier in Part I about stemflow sampling problems, the number of trees used in each plot was decided arbitrarily. However, it can be seen from Table 3 that the sample size chosen (i.e. five trees per plot) was comparable to that employed in other experiments undertaken by various investigators. Although it would have been desirable to have used a larger number of trees, this was not practical because of the time factor. The present sampling density was possibly the largest one that could be coped with, and it was assumed that sampling with five trees per plot was sufficient. Considering the small role of stemflow in comparison with precipitation, this assumption seemed justifiable.

III.3.4 Procedure of Stemflow Measurement

Stemflow measurement was made at weekly intervals on the same days as for gross precipitation and throughfall. Data was gathered for a period of 16 months from 24 June 1977 to 4 October 1978 with the exception of two interruptions:

i) 26 January - 1 March 1978; due to snow and frost.

ii) 29 July - 24 August 1978; due to the bursting of stemflow collars by tree growth.

On a typical measurement day, stemflow on each of the 45 sample trees was determined by weighing the containers into which it had been led by means of a manually operated spring balance. Each container was lifted and the weight was read and recorded. From this, the weight of the empty container was substracted to estimate the net stemflow water. Stemflow data obtained in this manner was then converted into milimetres of water-depth over the plot area. This was achieved by the addition of stemflow amounts in kilograms from five trees on the same plot and dividing this by the plot area. The areas of the plots were assessed by measurements on the ground of the estimated projection of the tree crowns on the plots.

PART IV

The preceding part of this thesis was concerned with the introduction and description of the instruments and measuring techniques that were used for assessing gross precipitation, throughfall and stemflow. Some statistical analyses were applied to various data to reveal the reliability and effectiveness of the sampling techniques, notably pertaining to the problem of how many gauges should be used to achieve accurate results. This part of the thesis, on the other hand, is concerned with the analysis of the data gathered in the field experiments. It also reports on the results of various aspects of interception values for the Pine forest and the deciduous species under study. It is convenient to present this material in three sections: one dealing with the results obtained in the Pine stand, one with the results obtained in the deciduous stands and a final one devoted to the comparison of findings and discussion of the role of interception in the water-balance of forests.

IV.1 Results of the Experiment undertaken in Pine

Results obtained from the experiment undertaken in the Pine stand are given in Table 15. The gross precipitation values in this table were estimated as the arithmetic means of the plastic funnel gauges installed at various locations at Dalmeny Estate. Average throughfall for each plot was estimated for each week as the mean of the seven gauges set on each plot. Average weekly stemflow values, on the other hand, were estimated by dividing the sum of stemflow measured on five trees on each sample plot by the plot areas which had previously been determined. The consequent determination of net precipitation and interception values was achieved according to Formulas 2 and 3. In these determinations, it was assumed that the same amount of rainfall fell on the forest canopy on all sample plots. This assumption may be in error, however, and will be discussed later in this section. Data obtained and the above described computations cannot be presented in this thesis due to its large volume. However, an example for the period of 6th October to 10th October 1977 is given in Table 16.

It can be seen from Table 15 that differences occurred between the plots in terms of both throughfall and stemflow. They were naturally reflected as differences in net precipitation and interception estimates. A study of Table 15 reveals that on 18 occasions out of 38, Plot 1 on the forest edge received the highest throughfall. On another set of 18 occasions, maximum throughfall was measured on Plot 2. Whereas on only one occasion was throughfall greater on Plot 3 than the other plots. During the remaining one occasion, equal throughfall was measured on Plots 1 and 2, the amount being greater than that at Plot 3.

Table 15 The Results of The Experiment Undertaken in Pine. G=Gross Precipitation, T=Throughfall, S=Stemflow, N=Net Precipitation, I=Interception. All in millimetres.

		Plot 1				Plot 2				Plot 3			
Period	G	T	S	N	I	T	S	N	I	T	S	N	I
6.5.1977-12.5.1977	7.1	3.4	-	-	-	2.5	-	-	-	1.5	-	-	-
13.5.1977-18.5.1977	8.3	3.6	-	-	-	5.0	-	-	-	2.8	-	-	-
19.5.1977-26.5.1977	1.8	1.4	-	-	-	1.3	-	-	-	0.4	-	-	-
27.5.1977-8.6.1977	35.7	27.3	-	-	-	26.6	-	-	-	20.2	-	-	-
9.6.1977-23.6.1977	40.9	32.0	-	-	-	38.8	-	-	-	24.9	-	-	-
24.6.1977-29.6.1977	7.9	4.1	0.0	4.1	3.8	5.0	0.0	5.0	2.9	6.1	0.0	6.1	1.8
30.6.1977-6.7.1977	3.0	2.6	0.0	2.6	0.4	1.7	0.0	1.7	1.3	0.8	0.0	0.8	2.2
14.7.1977-19.7.1977	15.5	7.7	0.1	7.8	7.7	7.4	0.1	7.5	8.0	5.2	0.1	5.3	10.2
20.7.1977-26.7.1977	9.1	3.9	0.1	4.0	5.1	3.4	0.0	3.4	5.7	2.0	0.0	2.0	7.1
3.8.1977-9.8.1977	14.6	6.6	0.2	6.8	7.8	6.0	0.1	6.1	8.5	4.3	0.0	4.3	10.3
16.8.1977-23.8.1977	11.6	5.9	0.0	5.9	5.7	7.9	0.0	7.9	3.7	4.6	0.0	4.6	7.0
24.8.1977-6.9.1977	59.0	39.6	0.6	40.2	18.8	46.4	0.2	46.6	12.4	32.9	0.3	33.2	25.8

Continued/. . .

<u>Table 15</u>

Period	G	Plot 1				Plot 2				Plot 3			
		T	S	N	I	T	S	N	T	T	S	N	I
7.9.1977-13.9.1977	20.0	9.6	0.4	10.0	10.0	7.3	0.1	7.4	12.6	5.7	0.0	5.7	14.3
21.9.1977-29.9.1977	32.9	24.7	0.9	25.6	7.3	26.5	0.3	26.8	6.1	23.4	0.6	24.0	8.9
30.9.1977-5.10.1977	20.2	12.9	1.0	13.9	6.3	11.9	0.3	12.2	8.0	7.3	0.2	7.5	12.7
6.10.1977-10.10.1977	54.6	44.4	1.9	46.3	8.3	46.7	1.0	47.7	6.9	40.3	1.7	42.0	12.6
19.10.1977-25.10.1977	6.2	1.4	0.0	1.4	4.8	2.4	0.0	2.4	3.8	1.1	0.0	1.1	5.1
26.10.1977-1.11.1977	51.9	47.4	2.5	49.9	2.0	47.3	1.7	49.0	2.9	42.4	2.5	44.9	7.0
2.11.1977-8.11.1977	33.6	15.9	0.7	16.6	17.0	17.1	0.2	17.3	16.3	13.8	0.1	13.9	19.7
9.11.1977-15.11.1977	34.5	25.1	1.2	26.3	8.2	24.3	0.5	24.8	9.7	19.0	0.5	19.5	15.0
16.11.1977-22.11.1977	6.1	3.5	0.0	3.5	2.6	4.5	0.0	4.5	1.6	2.7	0.0	2.7	3.4
23.11.1977-6.12.1977	10.9	7.9	0.8	8.7	2.2	5.8	0.2	6.0	4.9	3.6	0.2	3.8	7.1
7.12.1977-13.12.1977	26.4	14.6	0.6	15.2	11.2	18.5	0.1	18.6	7.8	13.7	0.2	13.9	12.5
22.12.1977-30.12.1977	18.9	9.7	0.0	9.7	9.2	11.8	0.0	11.8	7.1	8.1	0.0	8.1	10.8
31.12.1977-25.1.1978	40.5	25.0	1.5	26.5	14.0	20.3	0.7	21.0	19.5	18.1	0.6	18.7	21.8

Continued/. . .

Table 15

Period	G	Plot 1				Plot 2				Plot 3			
		T	S	N	I	T	S	N	I	T	S	N	I
2.3.1978-8.3.1978	6.5	1.4	0.0	1.4	5.1	1.6	0.0	1.6	4.9	1.4	0.0	1.4	5.1
9.3.1978-17.3.1978	16.9	9.1	0.1	9.2	7.7	9.2	0.1	9.3	7.6	6.8	0.1	6.9	10.0
18.3.1978-25.3.1978	20.1	10.7	0.8	11.5	8.6	9.0	0.1	9.1	11.0	6.4	0.0	6.4	13.7
26.3.1978-31.3.1978	11.0	5.6	0.4	6.0	5.0	4.4	0.1	4.5	6.5	2.9	0.0	2.9	8.1
1.4.1978-9.4.1978	10.9	7.5	0.2	7.7	3.2	9.7	0.0	9.7	1.2	6.5	0.1	6.6	4.3
10.4.1978-17.4.1978	3.1	1.5	0.0	1.5	1.6	1.4	0.0	1.4	1.7	1.1	0.0	1.1	2.0
26.4.1978-3.5.1978	35.5	25.4	1.3	26.7	8.8	24.1	0.5	24.6	10.9	22.4	0.8	23.2	12.3
4.5.1978-10.5.1978	6.9	3.5	0.0	3.5	3.4	4.1	0.0	4.1	2.8	3.0	0.0	3.0	3.9
11.5.1978-24.5.1978	18.9	10.6	0.2	10.8	8.1	11.9	0.1	12.0	6.9	8.6	0.1	8.7	10.2
1.6.1978-6.6.1978	6.9	3.1	0.0	3.1	3.8	3.1	0.0	3.1	3.8	2.3	0.0	2.3	4.6
15.6.1978-28.6.1978	52.0	33.9	0.2	34.1	17.9	38.9	0.2	39.1	12.9	30.6	0.1	30.7	21.3
29.6.1978-5.7.1978	27.0	15.9	0.1	16.0	11.0	14.7	0.1	14.8	12.2	12.1	0.0	12.1	14.9
19.7.1978-28.7.1978	26.0	12.8	0.0	12.8	13.2	15.5	0.0	15.5	10.5	11.1	0.1	11.2	14.8

Continued/. . .

Table 15

Period	G	Plot 1				Plot 2				Plot 3			
		T	S	N	I	T	S	N	I	T	S	N	I
29.7.1978-17.8.1978	50.5	-	-	-	-	-	-	-	-	-	-	-	-
18.7.1978-24.8.1978	12.5	-	-	-	-	-	-	-	-	-	-	-	-
25.8.1978-12.9.1978	48.6	-	1.1	-	-	-	0.4	-	-	-	0.2	-	-
13.9.1978-19.9.1978	9.0	-	0.2	-	-	-	0.0	-	-	-	0.0	-	-
20.9.1978-4.10.1978	38.2	-	0.5	-	-	-	0.3	-	-	-	0.3	-	-

Table 16 Computation of Average Gross Precipitation, Throughfall, Stemflow and Interception from Data collected on a Weekly Basis. An example for 6.10-10.10.1977

Gross Precipitation at Dalmeny

Gauge No	Gauge Reading(mm)
1	54.5
2	54.5
3	54.0
4	55.5
MEAN	54.6

Throughfall Under Pine

	Gauge Reading(mm)		
Gauge No	Plot 1	Plot 2	Plot 3
1	36.0	42.0	46.0
2	50.0	49.0	48.0
3	50.0	54.0	28.0
4	52.0	45.0	37.0
5	43.0	40.0	44.0
6	40.0	52.0	40.0
7	40.0	45.0	39.0
MEAN	44.4	46.7	40.3

Continued/. . .

Table 16 (Cont'd)

Stemflow on Pine

Gauge No	Stemflow Water(kg) Plot 1	Plot 2	Plot 3
1	9.6	2.6	19.1
2	11.1	28.6	19.6
3	28.6	2.6	7.1
4	17.6	6.6	28.6
5	4.6	1.1	7.6
TOTAL STEMFLOW(kg)	71.5	41.5	82.0
PLOT AREA(m^2)	37.2	41.3	48.2
STEMFLOW(mm)	1.9	1.0	1.7

Estimation of Interception

Gross Precipitation - (Throughfall + Stemflow) = Interception

Plot 1 54.6-(44.4+1.9)=8.3mm.

Plot 2 54.6-(46.7+1.0)=6.9mm.

Plot 3 54.6-(40.3+1.7)=12.6mm.

Table 15 also shows that a very small portion of rainfall became stemflow. The highest value obtained was 1.9mm for Plot 1 for the period 6 October to 10 October 1977 during which 54.6mm precipitation was recorded. Although differences in stemflow occurred between the plots, they were not large enough to alter the pattern of throughfall considerably. For this reason, net precipitation values are very similar to those of throughfall. The distribution of interception, on the other hand, is the reciprocal of that of net precipitation and throughfall, i.e. interception was highest where least net precipitation was measured. It can be concluded from the results presented in Table 15 that a greater portion of precipitation reached the forest floor on Plots 1 and 2, which were located on the forest edge and at 50m distance respectively. On the other hand, a smaller portion became net precipitation on Plot 3 in the interior of the forest.

Differences between the plots seem, in the first instance, to suggest that there may be a pattern of interception increasing from the forest edge towards the interior. However, a definite conclusion on such a pattern requires that some important questions be answered. Firstly, the accuracy and reliability of the results given in Table 15 ought to be tested so as to find out whether this pattern is a real one or whether it is a result of inaccurate measurements of gross precipitation throughfall and stemflow. Secondly, it should also be established whether the assumption of even distribution of precipitation over the plots is valid. This is necessary because, as has already been mentioned, the interception values were based on the assumption that all plots received the same amount of rainfall. The following sections are concerned with the analyses necessary to throw light on these questions.

IV.1.1 Accuracy of Gross Precipitation Measurement

It has already been discussed in I.2.1.1.1 that there is often an uncertainty in rainfall readings in a raingauge installed at some height above the ground. This is due to a wind effect which leads to underestimation of precipitation. Rodda (1967), for example, reported a reduction of 6.6% for his 127mm standard raingauge set at 30.5cm height in comparison with a ground level gauge. However, data obtained from the present experiment does not allow such comparison to be made since no ground level gauge was employed. It must be assumed therefore that the gross precipitation values in Table 15 could be in error by 6 to 7%. This in turn means that the interception values could well be underestimated.

Another source of error lies in the assumption adopted for gross precipitation that measurement outside the forest gives the amount of rainfall that really falls on the forest canopy. It has already been mentioned that it is difficult to achieve accurate rainfall measurement at canopy level. This is due to wind effect and instrumental error (see I.2.1.1.1). For this reason, gross precipitation is often measured outside forests or in forest openings. However, Helvey and Patric (1965 a) concluded that these measurements were accurate enough. The same procedure was also employed in the present experiment. Although it can be envisaged that the results obtained by this technique may be different from that amount of precipitation which actually landed on the forest canopy, the amount of error cannot be known.

In addition, there is also a need for discussion as to whether rainfall was distributed evenly over the plots. It has already been shown that rainfall readings from gross precipitation gauges at various locations on the experimental site showed only small differences. It can therefore be concluded that precipitation did not vary considerably from one place to another within the experimental site. However, this by no means shows that the same amount of rainfall really fell on the Pine plots where throughfall and stemflow were measured. It is likely that the spacial distribution of rainfall was affected by the presence of a forest edge. The effect can be thought, for example, as such that forest edge can often cause extra turbulence of air. In such a situation, some of the raindrops can be blown towards the tree crowns on the forest margin resulting in a greater amount of precipitation than the interior parts of the forest. Given the favourable location of the Pine forest at the present experimental site, such edge effect seemed more likely to take place in association with strong westerly winds. However, it was difficult to make any quantitative assessment of this. On a few occasions, it was observed that throughfall gauges installed on Plot 1 received some direct rainfall blown into them by westerly winds. However, it can be stated that water gained in this way was negligible.

IV.1.2 Statistical Tests of Significance of Differences between the Plots

In order to explain the differences shown in Table 15, the reliability of both throughfall and stemflow data must also be discussed, and the differences between the plots tested by statistical methods to indicate whether they are significant differences or whether they can be attributed to uncertainties or inaccuracies in the data.

It has already been shown in III.2.1 that accurate measurement of throughfall with 5% error at 95% probability required a large number of raingauges. However, sufficient numbers of gauges were employed to sample throughfall with an error of less than 10% at high probability levels (see Figure 13). In order to find out whether differences in throughfall between the plots resulted from this sampling error, statistical tests were applied to the weekly throughfall data. One such test was the analysis of variance (Snedecor and Cochran, 1967). The results obtained are given in Table 17. In these analyses, the three plots were regarded as "treatments" and the seven gauges as "replicates". The results show that on 28 occasions out of 38, differences between the plots were significant at the probability of 95%. On 10 occasions, throughfall showed no significant difference. This may be interpreted as indicating that the plots differed significantly in terms of throughfall.

Throughfall data was further analysed by the methods of the Least Significant Difference (LSD) and the Studentized Range (D). These methods were used to compare mean throughfall values for the plots. A full description of the methods can be found in Snedecor and Cochran (1967). In order to apply the tests, the following procedure was followed. Throughfall readings made at each of the 21 gauges on the three plots were summed for the whole experimental period except for the first five weeks (because only four gauges on each plot were used for those weeks). The results are a series of periodical throughfall values for each gauge

__Table 17__ **Results of Analysis of Variance applied to Throughfall Data for Pine (Plots 1, 2 and 3)**. f_1 and f_2 are degrees of freedom between and within classes respectively.

Period	f_1	f_2	F	P
6.5.1977 - 12.5.1977	2	9	14.54	0.000 *
13.5.1977 - 18.5.1977	2	9	5.74	0.020 *
19.5.1977 - 26.5.1977	2	9	11.49	0.000 *
27.5.1977 - 8.6.1977	2	9	7.33	0.010 *
9.6.1977 - 23.6.1977	2	9	5.11	0.030 *
24.6.1977 - 29.6.1977	2	18	3.61	0.050 *
30.6.1977 - 6.7.1977	2	18	32.83	0.001 *
14.7.1977 - 19.7.1977	2	18	5.59	0.010 *
20.7.1977 - 26.7.1977	2	18	7.91	0.000 *
3.8.1977 - 9.8.1977	2	18	3.35	0.060
16.8.1977 - 23.8.1977	2	18	8.53	0.000 *
24.8.1977 - 6.9.1977	2	18	7.41	0.000 *
7.9.1977 - 13.9.1977	2	18	10.11	0.000 *
21.9.1977 - 29,9.1977	2	18	1.09	0.400
30.9.1977 - 5.10.1977	2	18	27.02	0.000 *
6.10.1977 - 10.10.1977	2	18	2.03	0.200
19.10.1977- 25.10.1977	2	18	7.78	0.000 *
26.10.1977- 1.11.1977	2	18	2.60	0.100
2.11.1977 - 8.11.1977	2	18	1.67	0.200
9.11.1977 - 15.11.1977	2	18	4.55	0.020 *
16.11.1977- 22.11.1977	2	18	8.46	0.000 *
23.11.1977- 6.12.1977	2	18	17.41	0.000 *

Continued /...

Table 17 (Cont'd)

Period	f_1	f_2	F	P
7.12.1977 - 13.12.1977	2	18	4.48	0.030 *
22.12.1977 - 30.12.1977	2	18	7.35	0.000 *
31.12.1977 - 25.1.1978	2	18	9.44	0.000 *
2.3.1978 - 8.3.1978	2	18	0.51	0.600
9.3.1978 - 17.3.1978	2	18	5.21	0.020 *
18.2.1978 - 25.3.1978	2	18	12.84	0.000 *
26.3.1978 - 31.3.1978	2	18	13.14	0.000 *
1.4.1978 - 9.4.1978	2	18	3.01	0.070
10.4.1978 - 17.4.1978	2	18	4.39	0.030 *
26.4.1978 - 3.5.1978	2	18	1.21	0.300
4.5.1978 - 10.5.1978	2	18	4.61	0.020 *
11.5.1978 - 24.5.1978	2	18	4.03	0.040 *
1.6.1978 - 6.6.1978	2	18	2.28	0.100
15.6.1978 - 28.6.1978	2	18	3.87	0.040 *
29.6.1978 - 5.7.1978	2	18	2.79	0.090
19.7.1978 - 28.7.1978	2	18	4.85	0.020 *

* 28 Cases out of 38, $P < 0.05$ (significant at 95%)

which is shown in Table 18. Then the tests of LSD and D were applied to these values. According to these tests, a difference between any pair of mean values is declared as significant if it is greater than the calculated LSD and D values. Table 18 shows that differences between Plot 3 and both Plots 1 and 2 complied with this rule. Thus they are significant at 95% probability. The difference between Plot 1 and Plot 2, on the other hand, is exceeded by LSD and D - thus insigificant. It can be seen from Table 18 that the Studentized Range (D) is a more conservative test than the LSD one. Nevertheless, they both yielded the same result which leads to the conclusion that Plot 3 differed significantly from Plots 1 and 2. This was also confirmed by the result of the analysis of variance applied to the same data shown in Table 18 which gave significant result at $P = 0.005$.

The results of the tests applied so far suggest that the differences in throughfall values shown in Table 15 are real and significant between Plot 3 and both Plots 1 and 2. It might be thought that the same tests should also be applied to stemflow data. However, this is not necessary because it has been shown that stemflow on Pine is negligible and plays an insignificant role in determining net precipitation and interception. For this reason, stemflow data was not further tested.

Having tested the significance and reliability of the differences between the plots, it is now appropriate to look at total gross precipitation, throughfall and stemflow values for the whole experimental period. Weekly values in Table 15 were totalled for each component and the results are shown in Table 19. The periods for which the throughfall and stemflow

Table 18 Test of Significance of Periodical Throughfall at Three Pine Plots by Means of the Tests of Least Significant Difference(LSD) and Studentized Range(D). (After Snedecor & Cochran, 1967)

Gauge No	Plot 1	Plot 2	Plot 3	TOTAL
1	432.4	428.1	360.5	
2	507.9	497.5	377.6	
3	431.1	477.4	277.2	
4	520.8	451.7	353.5	
5	433.0	461.2	391.9	
6	381.5	541.0	420.3	
7	467.8	412.9	411.2	
$\Sigma X =$	3174.5	3269.8	2592.2	9036
$\bar{X}$	453.5	467.1	370.3	1290
ΣX^2	1453880	1538592	973667	3966139
$(\Sigma X)^2/n$	1439182	1527557	959781	3926520
Σx^2	14698	11035	13886	39619
d.f.	6	6	6	18

Pooled $s^2=39619/18=2201$ $s_D=\sqrt{2s^2/7}=25.1$

LSD=52.7 D=64.01

Plot 1 - Plot 3 = 83.2 *

Plot 2 - Plot 3 = 96.8 *

Plot 1 - Plot 2 = 13.6

(*) Significant at the 95% probability level.

Table 19 Summary of the Results of the Throughfall and Stemflow Measurements in Pine at Dalmeny.

Period: From 6 May 1977 to 28 July 1978

	Gross Precipitation (mm)	Throughfall (mm)	Throughfall (%)
Plot 1	812.9	521.2	64
Plot 2	812.9	544.0	67
Plot 3	812.9	420.1	52

Period: From 24 June 1977 to 4 October 1978

	Gross Precipitation (mm)	Stemflow (mm)	Stemflow (%)
Plot 1	814.9	17.6	2
Plot 2	814.9	7.4	1
Plot 3	814.9	8.8	1

data are available do not coincide. Nevertheless in both cases, gross precipitation amounted to over 800mm. 64% and 67% of rainfall became throughfall on Plots 1 and 2 respectively whilst it amounted to only 52% for Plot 3. The marked difference is apparent, which corresponds to a difference in absolute value of over 100mm between Plot 3 and both Plots 1 and 2. In the light of the statistical tests, this difference is considered to be real and significant. Having reached this conclusion, we have to investigate what caused such marked differences between the plots. The following further analysis and discussion are allocated to this topic. But it is useful first to look at some relationships of throughfall and stemflow.

IV.1.3 Relationship between Throughfall and Gross Precipitation

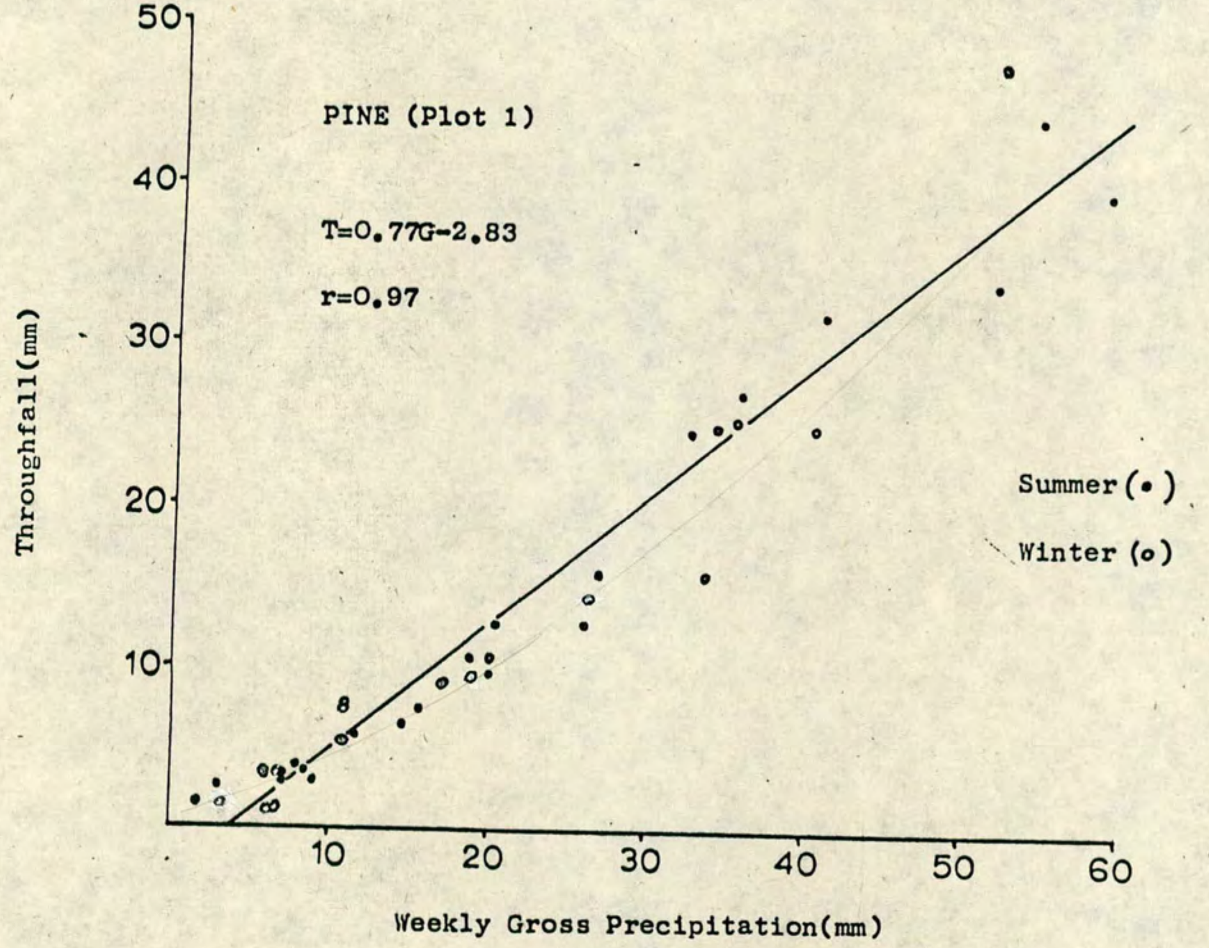
Work has been reported in the literature by many investigators relating throughfall to various factors which were considered to be independent in a statistical sense. One such attempt was made, for example, by Helvey and Patric (1965 a and b) who reported a positive correlation between throughfall and gross precipitation. Such relationships can be useful in the prediction of throughfall from gross precipitation data. This method is also of importance in comparing throughfall under different vegetation types or in different climatic regions.

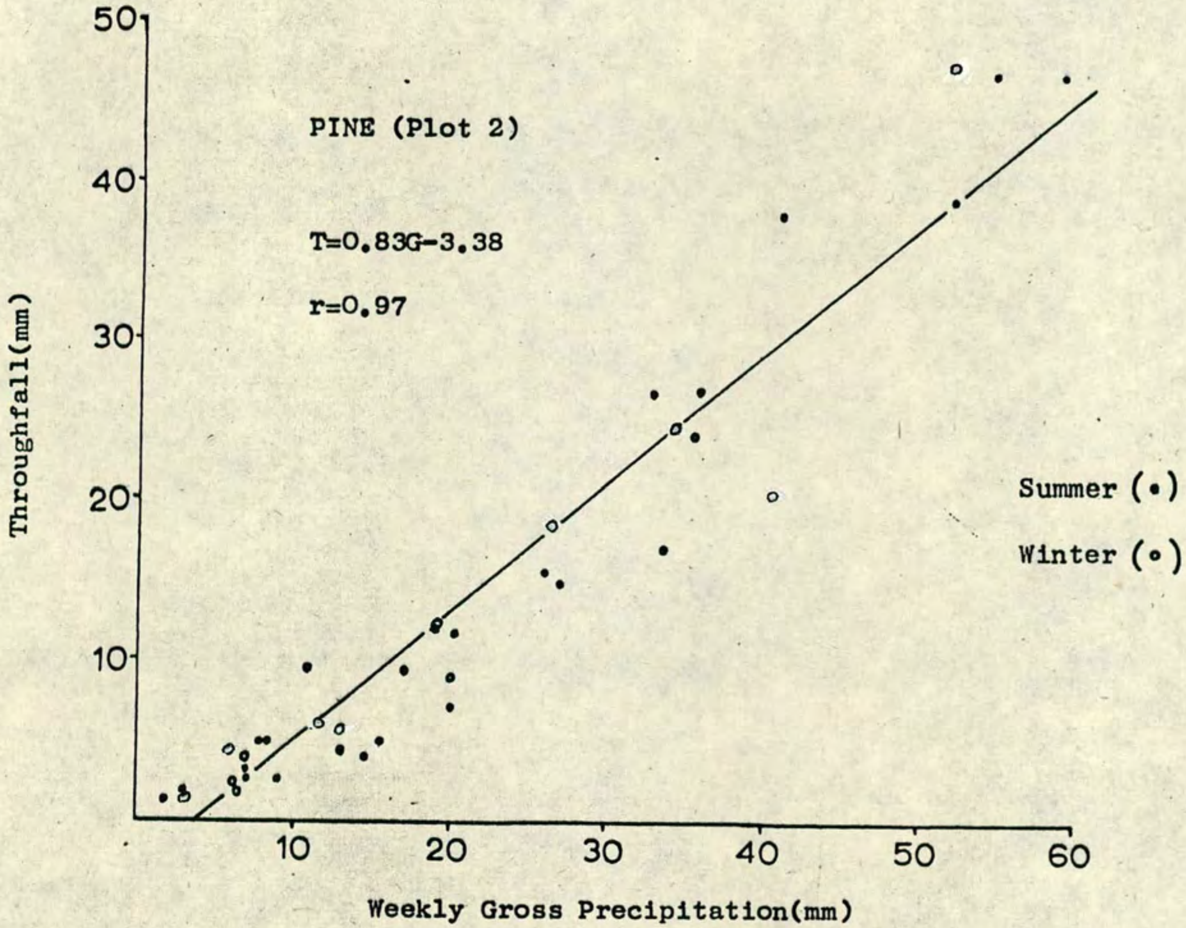
Close correlation between throughfall and gross precipitation was also found in the results obtained from the present experiment. In other words, the higher the rainfall during a weekly period the greater the amount of throughfall resulting from it. This is shown in Figure 24 where the scatter diagrams of throughfall for the three plots are given by plotting the throughfall values in Table 15 against the corresponding average gross precipitation. Analysis of regression was undertaken on the data for each plot and high correlation coefficients (0.96 and 0.97) were obtained. In these analyses, data was pooled regardless of season since, as can be seen from Figure 24, no seasonal variation could be detected. The results of these analyses are the regression equations given in Figure 24. Throughfall had regression slopes of 0.77, 0.83 and 0.68 for Plots 1, 2 and 3 respectively. Analysis of covariance was applied to test whether there were significant differences between the three equations. The results showed that the equation for Plot 3 differed significantly from both Plots 1 and 2 at $P = 0.01$. On the other hand, the difference between the equations for Plots 1 and 2 was found to be insignificant ($P = 0.50$).

IV.1.4 Relationship between Stemflow and Gross Precipitation

Stemflow was also plotted against gross precipitation in the same way as throughfall. The result is a scatter diagram for each stemflow plot (see Figure 25). It can be seen from these scatter diagrams that stemflow on Pine was not initiated by rainfall amounts of less than 10mm per week. This is due to the rough bark surface of this species, which holds up and absorbs considerable water before it starts to run down the tree trunks as stemflow. Regression analysis was applied to this data and relatively low correlation coefficients were obtained: 0.71, 0.69 and 0.63 for Plots 1, 2 and 3 respectively. The slopes of the

Figure 24 The Scatter Diagrams of Throughfall at The Pine Plots.




PINE (Plot 2)
T=0.83G-3.38
r=0.97
Throughfall(mm)
Weekly Gross Precipitation(mm)
Summer (•)
Winter (∘)
0
10
20
30
40
50
60

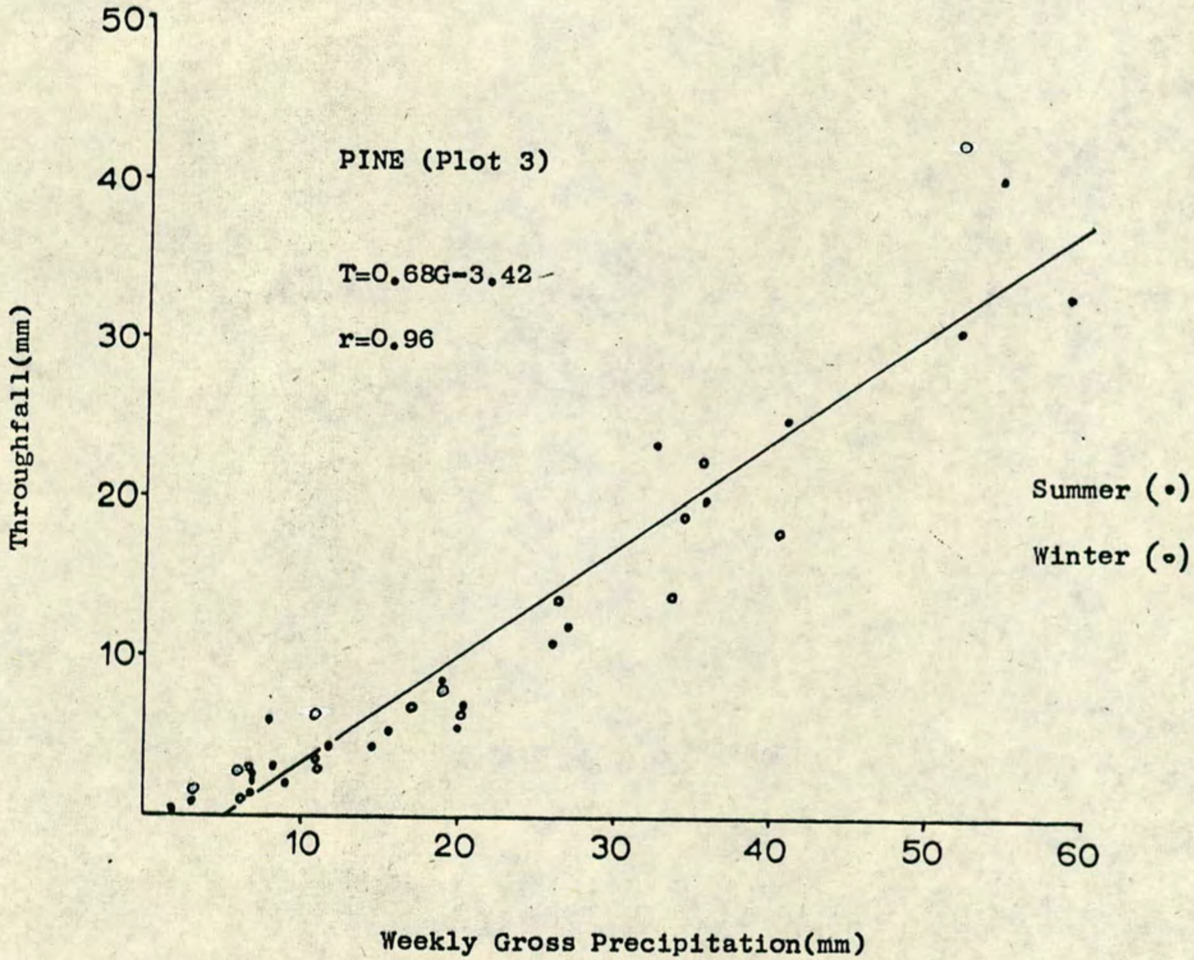
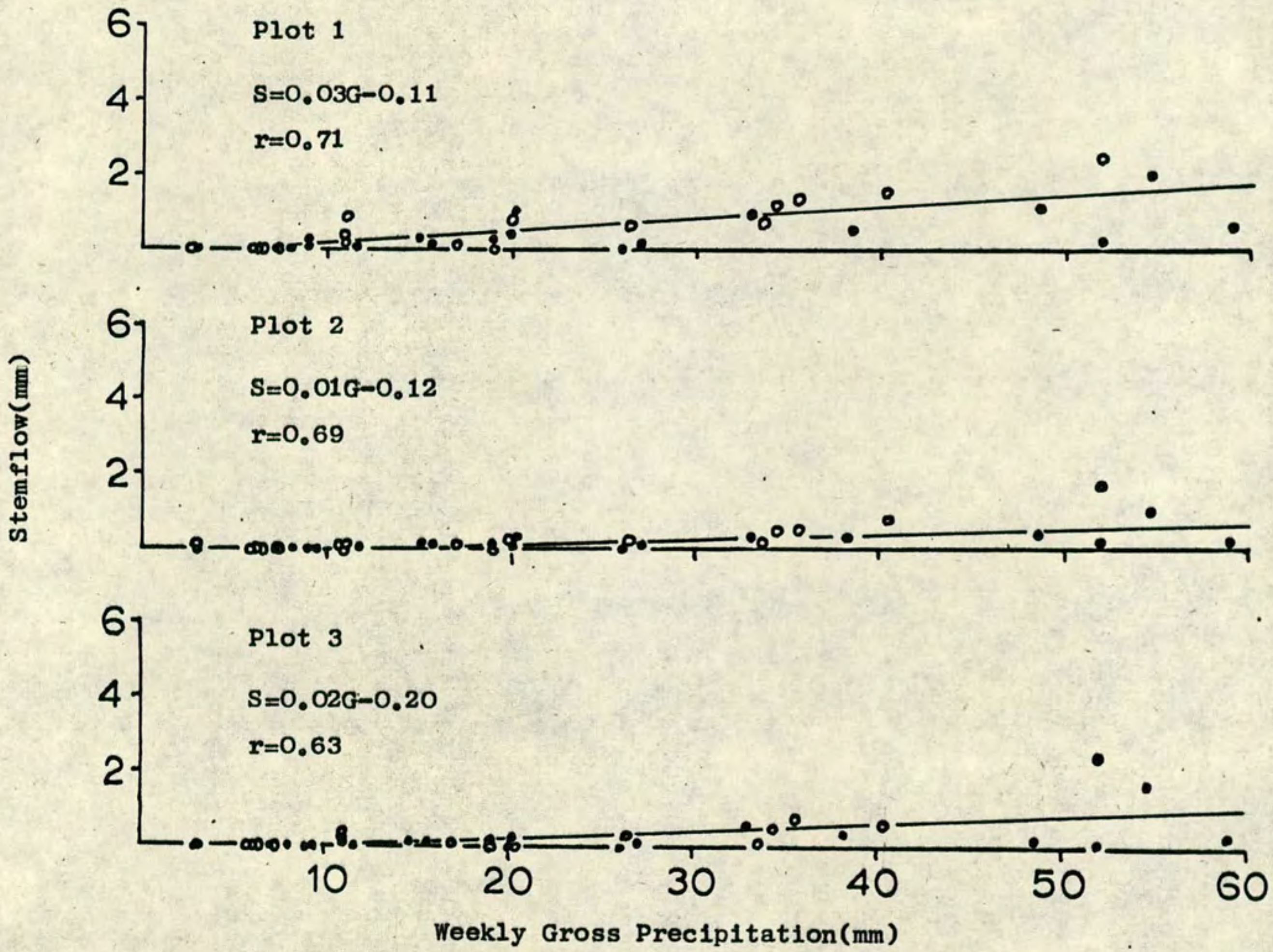

PINE (Plot 3)
T=0.68G-3.42
r=0.96
Summer (•)
Winter (∘)
Throughfall(mm)
Weekly Gross Precipitation(mm)
0
10
20
30
40
50
60

Figure 25 The Scatter Diagrams of Stemflow on Pine. Summer (•), Winter (∘).



regression equations are 0.03, 0.01 and 0.02 respectively. The equations suggest that a greater portion of precipitation became stemflow on Plot 1 than the others. This difference was tested by the analysis of covariance. The results showed that there were significant differences between the three equations. However, it can be concluded that although stemflow differed significantly amongst the plots, the net effect of stemflow on net precipitation reaching the soil was negligible. This conclusion seems rational in the light of the information given in Table 19 which shows that stemflow accounted for only 1 to 2% of precipitation.

IV.1.5 Interception Loss and its Partitioning into Canopy Storage and the Evaporation during Precipitation

Analysis of the data presented so far indicates that a greater part of the precipitation was intercepted by the Pine canopy on Plot 3 than on Plots 1 and 2, provided that the same amount of precipitation landed on all plots. This is shown in Table 20 where total interception amounts are given for the whole experimental period from 24 June 1977 to 28 July 1978. Interception accounted for 35% and 34% of gross precipitation on Plots 1 and 2 respectively, while it amounted to as much as 47% on Plot 3. In absolute values, this corresponds to a difference of over 90mm of rainfall. In the light of the statistical tests applied so far, this difference must be considered real and significant.

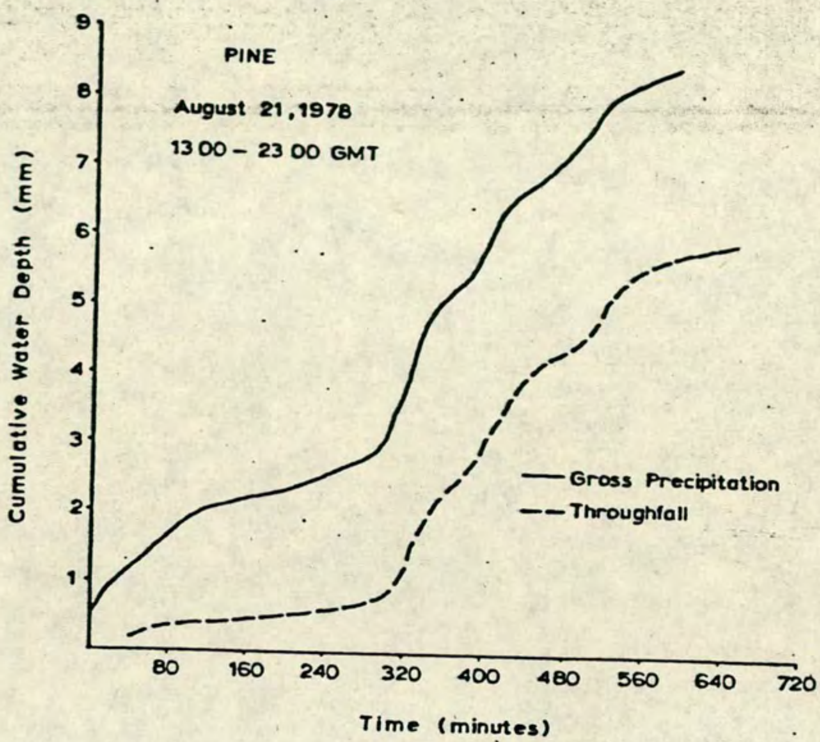
Having estimated the interception losses from the sample plots, it is useful to investigate what portions of these losses can be attributed to the canopy storage and evaporation during precipitation. In addition to providing useful information on these topics such an analysis may also help explain the differences occurring between the plots studied.

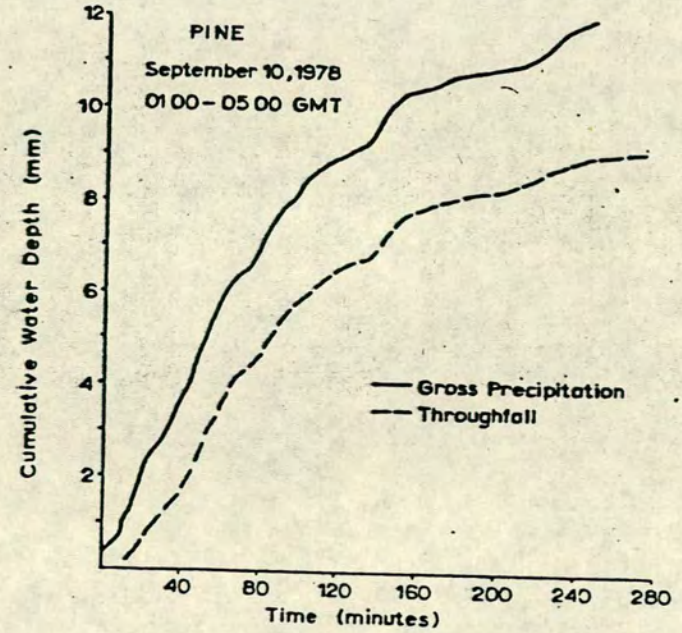
Table 20 Interception Values for the three Pine Plots for the Total Experimental Period of 24 June 1977 - 28 July 1978

		Interception	
	G(mm)	mm	%
Plot 1	719.1	249.8	35
Plot 2	719.1	242.6	34
Plot 3	719.1	340.5	47

It has already been mentioned that interception can be divided into two components. While some rainfall is detained by the trees as canopy storage, some water loss also takes place in the form of evaporation as precipitation continues to fall. Data obtained from the present study allowed such partitioning to be made quantitatively. This is best illustrated in Figure 26 where a detailed analysis of two typical rain events is presented by means of information obtained by the use of tipping-bucket raingauges. It is clear from Figure 26 that throughfall started some time after the commencement of precipitation due to canopy storage. The actual length of this lapse depended on the rainfall intensity, i.e. 40 minutes in the case of the shower of 21 August 1977, 15 minutes for the 10 September 1977 shower which was much heavier. It is also clear from Figure 26 that the initial difference between precipitation and throughfall increased on both occasions as the rainfall continued. This is attributable to the evaporation of intercepted water during precipitation.

Figure 26 Cumulative Gross Precipitation and Throughfall in Pine (Plot 2) during two individual Rain Events. Data from Tipping-Bucket Gauges





Canopy storage capacity has often been determined by an extrapolation of the regression equation of interception on gross precipitation (Zinke, 1967). This approach, however, could not be used in the present study because the data was collected on a weekly rather than on an event basis. Another method, on the other hand, has been suggested by Rutter (1963), which estimates canopy storage capacity from individual heavy showers with short duration for which evaporation during rainfall can be considered negligible. He described such suitable showers as those giving more than 5mm of rain and lasting less than three hours by day or six hours by night. Although the present weekly data often consisted of more than one rain event, it was possible to detect from the rainfall recorder charts that data for the week 30 June to 6 July 1977 resulted from only one rain event. Rainfall was measured to be 3.0mm with a duration of one hour. It can be seen from Table 15 that interception values for this period were 0.4mm, 1.3mm and 2.2mm for Plots 1, 2 and 3 respectively. Although this shower did not comply fully with Rutter's specifications, the values obtained from it were the only ones available. They were, therefore, accepted as usable canopy storage values - although it is recognized that they may be considerably in error.

An attempt based on the above canopy storage estimates was made to assess quantitatively what portions of interception loss could be attributed to the canopy storage and evaporation during precipitation. In order to achieve this, it was necessary to know how many times the canopy storage capacity was satisfied during the experimental period. Such information was gathered from the records of the Casella rain recorder and also from data collected by the

Meteorological Office at Turnhouse Airport. The results are shown in Table 21. In these estimates, it was assumed that the canopy storage capacity was fully satisfied by heavy rain shows, and that small showers (less than estimated canopy storage capacities) were completely caught by the forest canopy. The data in Table 21 clearly shows that the plots responded differently in intercepting precipitation. While only 76.1mm was retained as canopy storage on Plot 1, it amounted to 168.8mm and 261.5mm on Plots 2 and 3 respectively. As a result, the average evaporation rate from the wet canopy on Plot 1 during precipitation for the whole experimental period was 0.36mm/hour, whereas intercepted water on average evaporated at 0.15mm/hour and 0.16mm/hour from Plots 2 and 3 respectively. This is in fact what might be expected for Plot 1, being right on the forest edge, is more exposed and therefore experiences wind and radiation conditions likely to result in higher evaporation rates than those occurring at the other plots. It must be noted here that the above evaporation rates are average values for the whole period, the actual rates must have varied according to prevailing meteorological factors. (Rutter et. al. (1977) reported evaporation rates varying from 0.03mm/hour to 0.24mm/hour).

The assessment of the partitioning of interception presented above seems to have an important implication that the differences in interception values between the plots (particularly that of Plot 3) may be explained. It is apparent that they can be attributed to the results presented already that:

i) Greater interception loss (i.e. lesser throughfall) from Plot 3 was a result of greater canopy storage capacity

Table 21 Partitioning of Interception by Pine into Canopy Storage and Evaporation during Precipitation

Period: From 24 June 1977 to 28 July 1978

Gross Precipitation: 719.1mm

	Plot 1	Plot 2	Plot 3
Interception Loss	249.8mm	242.6mm	340.5mm
Water Loss due to Canopy Storage	76.1mm	168.8mm	261.5mm
Water Loss due to Evaporation (during Precipitation)	173.7mm	73.8mm	79.0mm
Total Rainfall Duration	483.9 hours	483.9 hours	483.9 hours
Average Evaporation Rate	0.36mm/hour	0.15mm/hour	0.16mm/hour

determined for this plot.

ii) Lesser interception occurred on Plot 1 on the forest edge despite higher evaporation rates due to exposure. It is therefore concluded that the differences between plots were due more to different canopy storage capacities than to evaporation during precipitation provided, of course, that precipitation fell over the whole forest canopy uniformly.

IV.2 Results of Experiments undertaken in the Deciduous Species

Data obtained from the weekly measurements of gross precipitation, throughfall and stemflow for the deciduous species were analyzed in the same way as for the Pine site to determine average values. The results are given in Table 22 for the three sites for each weekly period. In this table, gross precipitation values are the same as those shown already in Table 15 in the previous section on Pine. Throughfall values are the arithmetic means of all throughfall gauges installed in each site. In the case of the Sycamore in Compartment 11(S1), different sampling trechniques were used which, as has already been shown in Part III, did not yield significantly different results. For this reason, data obtained by different sampling techniques have been regarded as equally reliable, and have been pooled to determine weekly average throughfall values for S1. In this way, the accuracy is increased because the estimates are based on a larger number of gauges. Some of the throughfall values for S1 in Table 22 are therefore based on readings in 44 gauges, 21 of which were installed on the 0.5m grid and 23 in the triangular perspex trough. In the case of the other sites (Sycamore in Compartment 13 (S2) and young Beech in Compartment 11 (Be 2)), no such pooling was necessary since only one sampling technique was carried out at a time in each site. The stemflow results shown in Table 22 represent the data for the stemflow plots located in the inner part of Be 2 and S1. The results obtained from the stemflow plots on the forest edge were left out to ensure that the stemflow data used related as closely as possible to the plots where throughfall was measured, and not to those on the edge of the stand where

Table 22 The Results of The Experiments Undertaken in Deciduous Species. G=Gross Precipitation, T=Throughfall, S=Stemflow, N=Net Precipitation, I=Interception. All in millimetres.

		Beech (Be 2)				Sycamore (S 1)				Sycamore (S 2)			
Period	G	T	S	N	I	T	S	N	I	T	S	N	I
27.5.1977-8.6.1977	35.7	23.8	-	-	-	27.4	-	-	-	-	-	-	-
9.6.1977-23.6.1977	40.9	27.5	-	-	-	34.0	-	-	-	-	-	-	-
24.6.1977-29.6.1977	7.9	3.7	0.4	4.1	3.8	5.6	0.0	5.6	2.3	4.6	0.0	4.6	3.3
30.6.1977-6.7.1977	3.0	1.6	0.2	1.8	1.2	2.4	0.0	2.4	0.6	2.3	0.0	2.3	0.7
14.7.1977-19.7.1977	15.5	8.4	1.4	9.8	5.7	10.6	0.2	10.8	4.7	10.9	0.3	11.2	4.3
20.7.1977-26.7.1977	9.1	3.9	0.7	4.6	4.5	6.1	0.0	6.1	3.0	6.3	0.0	6.3	2.8
3.8.1977-9.8.1977	14.6	8.2	2.3	10.5	4.1	10.4	0.3	10.7	3.9	9.9	0.2	10.1	4.5
16.8.1977-23.8.1977	11.6	5.1	1.0	6.1	5.5	8.0	0.0	8.0	3.6	7.3	0.0	7.3	4.3
24.8.1977-6.9.1977	59.0	37.6	11.0	48.6	10.4	43.2	5.9	49.1	9.9	41.8	1.9	43.7	15.3
7.9.1977-13.9.1977	20.0	10.8	3.1	13.9	6.1	13.2	2.9	16.1	3.9	13.7	0.4	14.1	5.9
21.9.1977-29.9.1977	32.9	22.0	6.3	28.3	4.6	25.8	4.6	30.4	2.5	26.4	1.3	27.7	5.2
30.9.1977-5.10.1977	20.2	-	3.6	-	-	14.8	1.2	16.0	4.2	15.7	0.5	16.2	4.0
6.10.1977-10.10.1977	54.6	-	12.6	-	-	44.8	10.0	54.8	-0.2	35.8	2.5	38.3	16.3

Continued/. . .

Table 22

Period	G	Beech (Be 2)				Sycamore (S 1)				Sycamore (S 2)			
		T	S	N	I	T	S	N	I	T	S	N	I
19.10.1977-25.10.1977	6.2	-	0.1	-	-	3.8	0.1	3.9	2.3	3.8	0.0	3.8	2.4
26.10.1977-1.11.1977	51.9	-	11.2	-	-	41.4	7.5	48.9	3.0	42.5	2.9	45.4	6.5
2.11.1977-8.11.1977	33.6	-	4.0	-	-	25.5	1.5	27.0	6.6	28.8	0.9	29.7	3.9
9.11.1977-15.11.1977	34.5	-	6.8	-	-	28.6	4.0	32.6	1.9	28.5	1.7	30.2	4.3
16.11.1977-22.11.1977	6.1	-	0.9	-	-	5.3	0.4	5.7	0.4	5.0	0.2	5.2	0.9
23.11.1977-6.12.1977	10.9	-	1.7	-	-	8.2	0.5	8.7	2.2	9.0	0.4	9.4	1.5
7.12.1977-13.12.1977	26.4	-	5.3	-	-	19.6	3.8	23.4	3.0	20.6	1.4	22.0	4.4
22.12.1977-30.12.1977	18.9	-	3.1	-	-	15.1	2.0	17.1	1.8	16.2	0.5	16.7	2.2
31.12.1977-25.1.1978	40.5	-	5.0	-	-	31.7	2.1	33.8	6.7	33.9	0.7	34.6	5.9
2.3.1978-8.3.1978	6.5	-	0.4	-	-	5.4	0.1	5.5	1.0	5.4	0.0	5.4	1.1
9.3.1978-17.3.1978	16.9	-	2.3	-	-	15.2	0.5	15.7	1.2	15.4	0.1	15.5	1.4
18.3.1978-25.3.1978	20.1	10.7	2.5	13.2	6.9	16.8	1.0	17.8	2.4	17.3	0.4	17.7	2.4
26.3.1978-31.3.1978	11.0	6.5	1.0	7.5	3.5	9.7	0.3	10.0	1.0	9.9	0.1	10.0	1.0

Continued/. . .

Table 22

Period		Beech (Be 2)				Sycamore (S 1)				Sycamore (S 2)			
	G	T	S	N	I	T	S	N	I	T	S	N	I
1.4.1978-9.4.1978	10.9	5.1	2.1	7.2	3.7	8.9	2.6	11.5	-0.6	7.8	0.6	8.4	2.5
10.4.1978-17.4.1978	3.1	1.6	0.2	1.8	1.3	2.5	0.0	2.5	0.6	2.1	0.0	2.1	1.0
26.4.1978-3.5.1978	35.5	15.2	9.6	24.8	10.7	28.6	9.2	37.8	-2.3	24.2	2.9	27.1	8.4
4.5.1978-10.5.1978	6.9	3.4	0.7	4.1	2.8	6.3	0.2	6.5	0.4	5.5	0.0	5.5	1.4
11.5.1978-24.5,1978	18.9	11.5	2.5	14.0	4.9	16.3	0.8	17.1	1.8	16.6	0.3	16.9	2.0
1.6.1978-6.6.1978	6.9	2.7	0.4	3.1	3.8	5.4	0.0	5.4	1.5	5.0	0.0	5.0	1.9
15.6.1978-28.6.1978	52.0	28.5	6.6	35.1	16.9	44.2	3.6	47.8	4.2	39.8	0.7	40.5	11.5
29.6.1978-5.7.1978	27.0	13.0	6.0	19.0	8.0	22.6	1.3	23.9	3.1	17.9	0.4	18.3	8.7
19.7.1978-28.7.1978	26.0	12.4	2.3	14.7	11.3	19.6	1.2	20.8	5.2	18.0	0.4	18.4	7.6
29.7.1978-17.8.1978	50.5	28.9	-	-	-	39.3	-	-	-	38.6	-	-	-
18.8.1978-24.8.1978	12.5	6.5	-	-	-	10.1	-	-	-	9.1	-	-	-
25.8.1978-12.9.1978	48.6	26.0	9.5	35.5	13.1	37.9	3.2	41.1	7.5	35.4	1.5	36.9	11.7
13.9.1978-19.9.1978	9.0	3.3	1.0	4.3	4.7	6.5	0.1	6.6	2.4	5.6	0.1	5.7	3.3
20.9.1978-4.10.1978	38.2	19.1	8.2	27.3	10.9	31.1	2.6	33.7	4.5	27.6	1.4	29.0	9.2

conditions could be different. The estimation of net precipitation and interception loss was achieved in the same way as for the Pine site according to Formulae 2 and 3. In these estimations, it was assumed that the same amount of gross precipitation fell at each site.

It can be seen from Table 22 that differences occurred between the species of Sycamore and Beech in terms of both throughfall and stemflow. It can also be seen that similar differences also occurred between the two sycamore sites S1 and S2. It is only natural that the magnitude of these differences varied according to very complex conditions, notably to the varying weekly gross precipitation amount and the meteorological evaporative conditions. A preliminary study of the results given in Table 22 suggests that less throughfall occurred under Beech than Sycamore. Stemflow, on the other hand, was higher under Beech than Sycamore. However, the differences in stemflow are not large enough, on average, to offset differences in throughfall between the two species. Although differences are also evident between the two Sycamore sites (S1 and S2), they appear to be less marked and not consistent (i.e. not always in favour of a particular site).

It should be stated that on three occasions (weeks starting 6 October 1977, 1 April 1978 and 26 April 1978), the sum of throughfall and stemflow (i.e. net precipitation) exceeded the corresponding weekly gross precipitation values at the Sycamore plot in Compartment 11 (i.e. S1). This resulted in the estimation of negative interception. However, this by no means proves an extra water gain during those three periods. The same situations did not occur at other sites (including the Pine). It is therefore considered that these negative interception values are false as a result of sampling error. It is known from the literature, for example from Slatyer's (1965) work, that such discrepancies in interception data can occur. Slatyer (1965) carried out his experiment on Acacia aneura F.Muell and detected similar discrepancies in his data. He suggested however that such errors could not be attributed to errors involved in the area estimation of stemflow plots since this would be of a systematic nature. He, therefore, concluded that such errors could possibly have arisen from throughfall gauge readings. In the present case, it appears logical to consider that the discrepancies may be attributed to:

i) The high degree of scatter (variation) in throughfall readings.

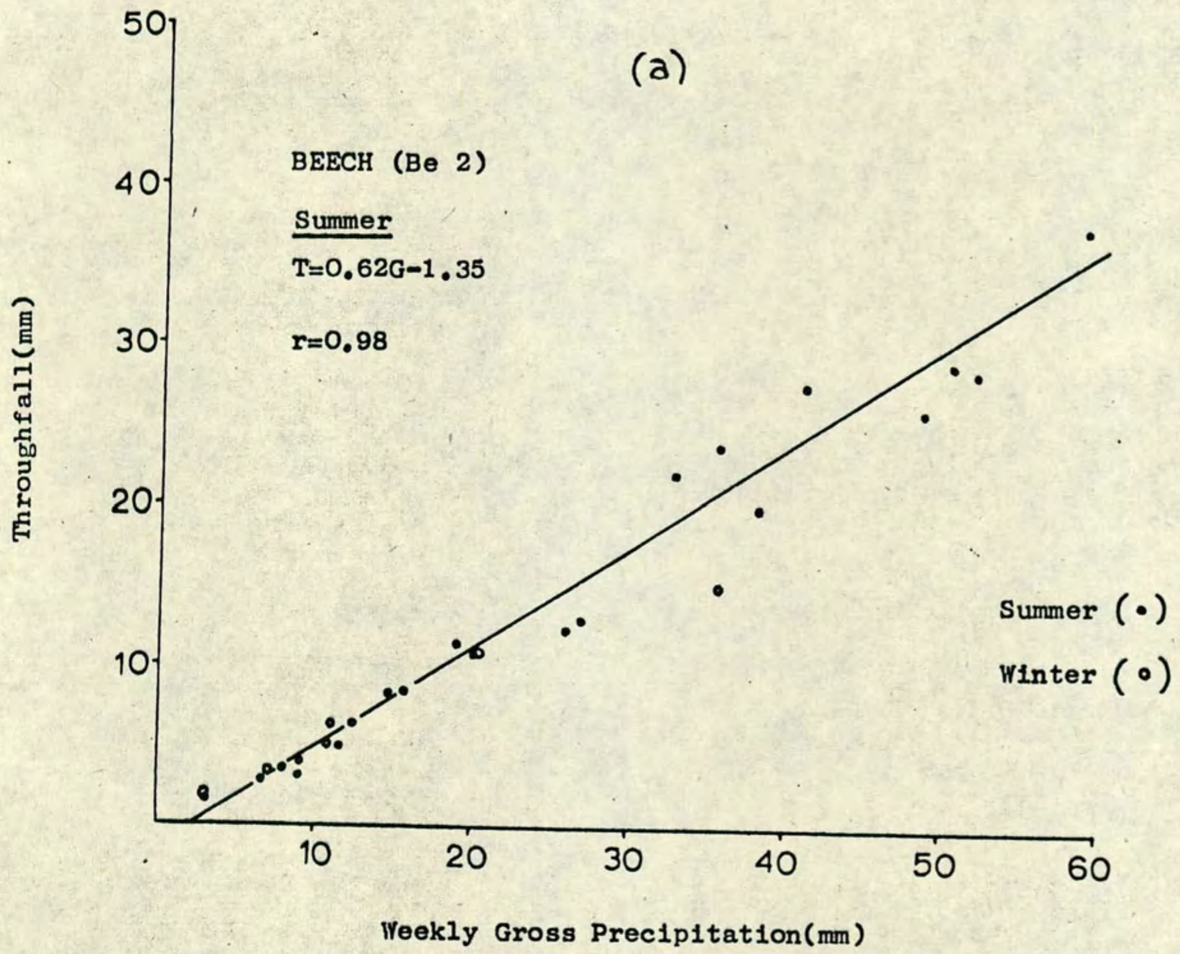
ii) The assumption of even distribution of gross precipitation over the site which probably was not valid during the three periods mentioned above. However, it is difficult to detect the exact source of the discrepancy. Fortunately, however, they did not occur often and the results given in Table 22 are generally free from such discrepancies. In the following tests, these discrepancies were handled by taking them to be zero.

It also seemed sensible to test the data for seasonal differences that might be expected to occur in deciduous trees due to their leafless state in the winter period.

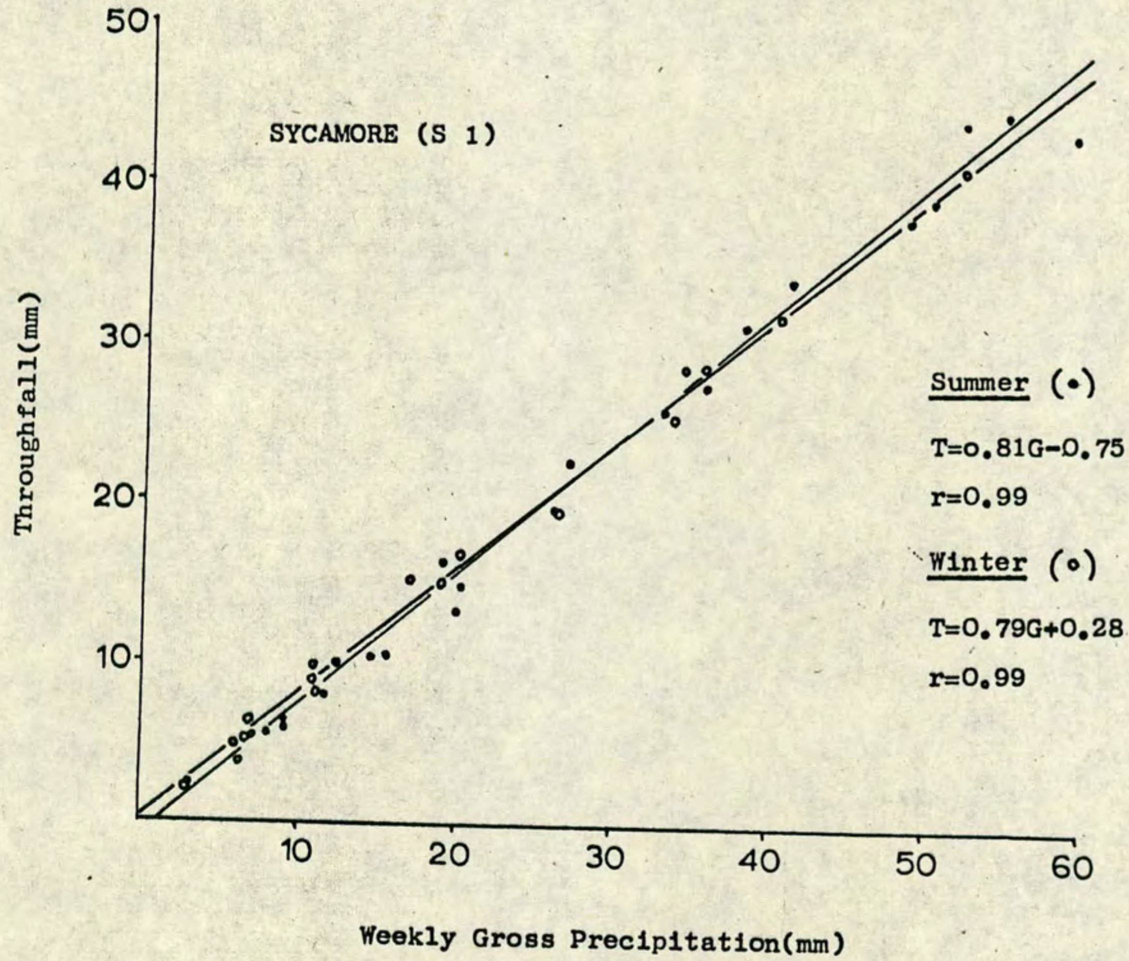
IV.2.1 Effect of the Leaf-Fall on Throughfall and Comparison between Species

The throughfall values given in Table 22 were plotted against the corresponding gross precipitation values to obtain the scatter diagrams for each site shown in Figure 27 (a,b,c). These diagrams clearly show a close positive correlation between the two variables. In the case of the Beech site (Be 2), only six data points were available for the winter (leafless) season which was not sufficient to draw definite conclusions about the effect of leaf-fall on throughfall. For this reason, regression analysis was applied only to the summer data and a close correlation coefficient was obtained ($r = 0.98$). The regression equation and its line are also shown in Figure 27(a). In the case of the two Sycamore sites, on the other hand, sufficient data were available for both dormant and growing seasons. Diagrams in Figure 27(b) and (c) appear to suggest that throughfall increased in proportion during winter when the trees were leafless. However, no marked difference between the two canopy stages is evident. To test the significance of the seasonal variations, the analysis of regression was applied separately to the throughfall data for the two Sycamore sites. Regression equations with $r = 0.99$ were calculated, the straight lines of which are also depicted in Figure 27(b) and (c). These two regression lines were compared by analysis of covariance which showed significant seasonal variation at the site in Compartment 13 (S2), whereas no significant difference could be detected at site S(1) in Compartment 11.

Figure 27 The Scatter Diagrams of Throughfall in Deciduous Species

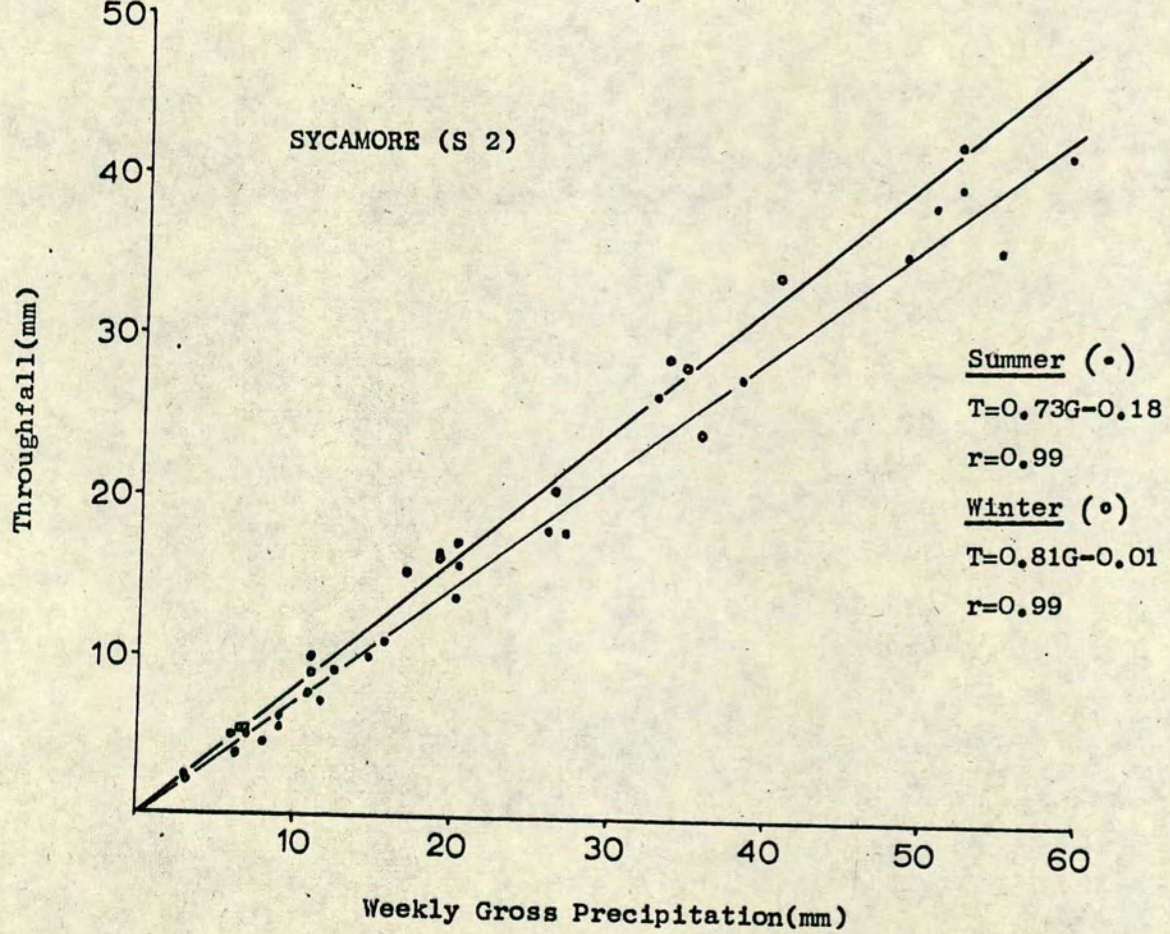


(b)



SYCAMORE (S 1)
Summer (•)
T=o.81G-0.75
r=0.99
Winter (o)
T=0.79G+0.28
r=0.99
Throughfall(mm)
Weekly Gross Precipitation(mm)
50
40
30
20
10
10
20
30
40
50
60

(c)


SYCAMORE (S 2)
Throughfall(mm)
Weekly Gross Precipitation(mm)
Summer (•)
T=0.73G-0.18
r=0.99
Winter (∘)
T=0.81G-0.01
r=0.99
10
20
30
40
50
60

In order to study the effect of leaf-fall in absolute terms, total throughfall values for the leafy and leafless periods were estimated from Table 22 and the results are given in Table 23. Figures in Table 23 clearly indicate that 78% and 80% of gross precipitation reached the forest floor at S(1) as throughfall in summer and winter seasons during which 614.6mm and 339.9mm rainfall was recorded respectively. In the light of the results of the analysis of covariance, the 2% difference can be considered insignificant. In the case of S(2), 538.0mm and 339.9mm rainfall fell during the two summer seasons and winter season respectively, and throughfall amounted to 72% and 81% respectively. This difference of 9% is considered to be real and significant. However, it was found difficult to explain why such different effects should occur between the two Sycamore sites. From the standpoint of the accuracy and reliability of the throughfall data, the results for S(1) should be regarded more reliable since a far larger number of gauges (44 against 11) was used at S(1) than S(2). When this is taken into account, it may be concluded that the seasonal variation in throughfall under the Sycamore trees should be considered insignificant.

Having studied the variations in throughfall due to leaf-fall, probable variations between the species of Sycamore and Beech can also be investigated by looking at the data already presented in Table 23. Ignoring the seasonal variations, the combined summer and winter data are presented in Table 23 as total values for the whole experimental period at each site. The figures clearly show that although on average 70% and 76% of gross precipitation was measured as throughfall under

Table 23 Seasonal Throughfall measured in the Deciduous Species

	Rainfall (mm)	Throughfall mm	Throughfall %
Sycamore (1)			
Summer	614.6	479.3	78
Winter	339.9	272.6	80
Total	954.5	751.9	79
Sycamore (2)			
Summer	538.0	388.3	72
Winter	339.9	275.9	81
Total	877.9	664.2	76
Beech (2)			
Summer	539.8	304.5	56
Winter	87.5	42.5	49
Total	627.3	347.0	55

Sycamore trees at sites S(1) and S(2) respectively, throughfall amounted only to 55% under Beech trees (Be 2). The marked difference between the species is evident. The analysis of covariance also provided a good means of testing the significance of the difference between the two species. To achieve this, seasonal variations were ignored and regression equations were calculated for each site regardless of leafy and leafless seasons. The resultant equations are:

Sycamore (1)	$T = 0.80G - 0.23$	$r = 0.99$	(13)
Sycamore (2)	$T = 0.75G + 0.22$	$r = 0.99$	(14)
Beech (2)	$T = 0.60G - 1.14$	$r = 0.98$	(15)

Then the regression equations were compared by analysis of covariance. The tests indicated significant differences at $p = 0.001$ in the slopes of regression equations between Beech and both Sycamore sites. The small difference between the two Sycamore sites, on the other hand, was found to be insignificant ($p > 0.05$). It is therefore concluded that significantly more throughfall occurred under the Sycamore trees than the Beech trees. This is probably attributable to the different leaf and branch structures of the two species. It must be stated that, in the case of the Beech site, the trees have a very close canopy with overlapping crowns. In the case of the Sycamore sites, on the other hand, the canopies are not as dense, and small inter-tree gaps exist. This can be seen from the hemispherical canopy photographs taken vertically on the forest floor at the three sites, enclosed in Appendix 1. It is also concluded that the small difference found between the two Sycamore sites is statistically insignificant and can be attributed to variations existing in the weekly throughfall readings within the sites (see Part III).

IV.2.2 Results of Stemflow Measurements on the Deciduous Trees

It can be seen from Table 22 that a considerable proportion of the weekly gross precipitation became stemflow on the deciduous trees, notably the Beech trees. On Beech, for example, 12.6mm stemflow was measured for the week starting 6 October 1977 during which 54.6mm of gross precipitation was recorded. It has already been shown in the previous section that the stemflow measured on Pine never exceeded 2.5mm for any weekly period of duration. This therefore shows important difference between the Pine and deciduous trees and draws attention to the significant role of stemflow in the distribution of rainfall falling on deciduous trees.

In order to reveal the magnitude and proportion of stemflow, total stemflow values were estimated from Table 22 for the whole experimental period as well as for the leafy and leafless periods separately. The results are given in Table 24 which clearly show that as much as 17% of gross precipitation ran down the Beech trees to become stemflow. This proportion was not influenced by leaf-fall. At the Sycamore site in Compartment 11 (S1), stemflow amounted to 8% and 11% for summer and winter respectively, against corresponding values of 3% and 4% for the other Sycamore site in Compartment 13 (S2). A slight increase during winter is evident, which can be attributed to the leafless branches being more exposed to direct rainfall thus catching and leading more water down the main trunk. However, it is clear from the figures in Table 24 that larger and more significant differences occurred between the sites, notably between Beech and

Table 24 Seasonal Stemflow Volumes measured on the Deciduous Species

		STEMFLOW					
		Sycamore (1)		Sycamore (2)		Beech (2)	
	Rainfall (mm)	mm	%	mm	%	mm	%
Summer	475.0	37.9	8	11.9	3	79.1	17
Winter	339.9	35.8	11	12.8	4	56.9	17
Total	814.9	73.7	9	24.7	3	136.0	17

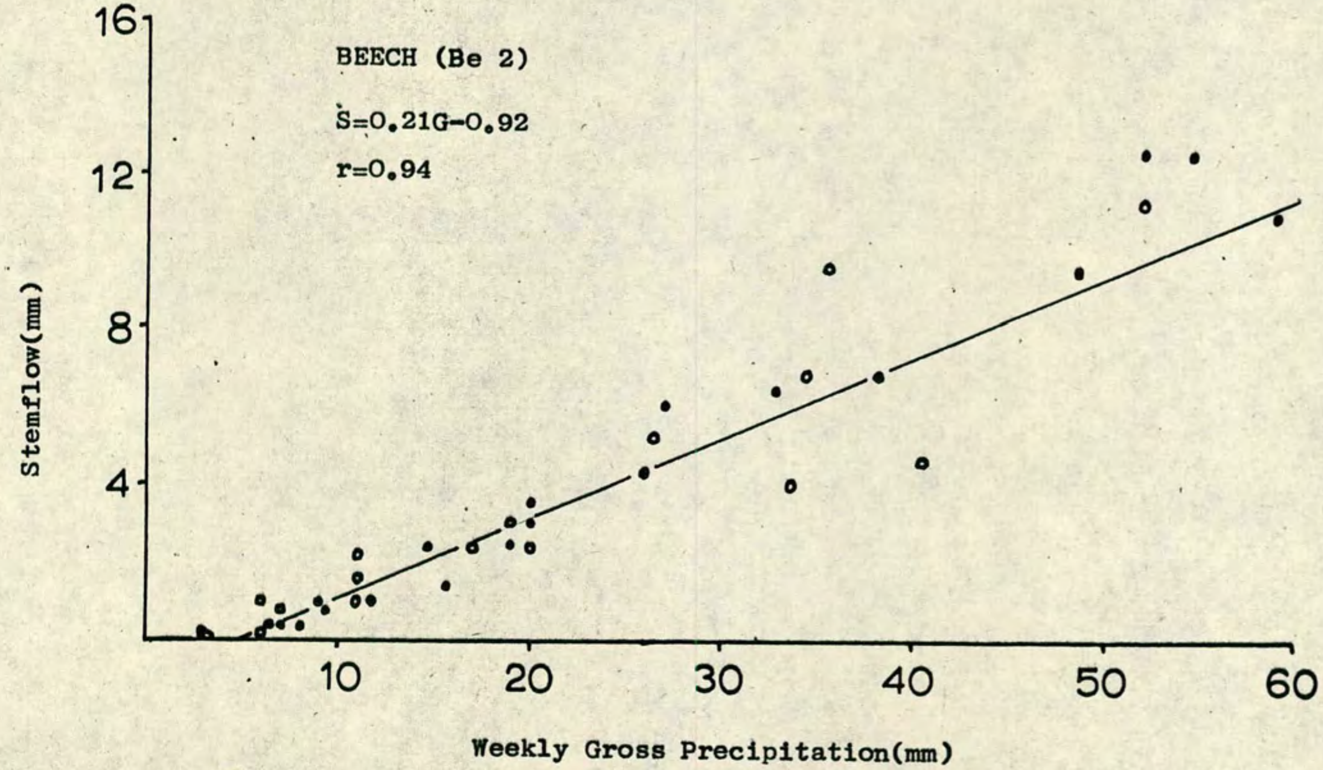
Sycamore sites. The greater capacity of the Beech trees to generate more stemflow may be attributed to their more numerous and much denser branching than the Sycamore trees.

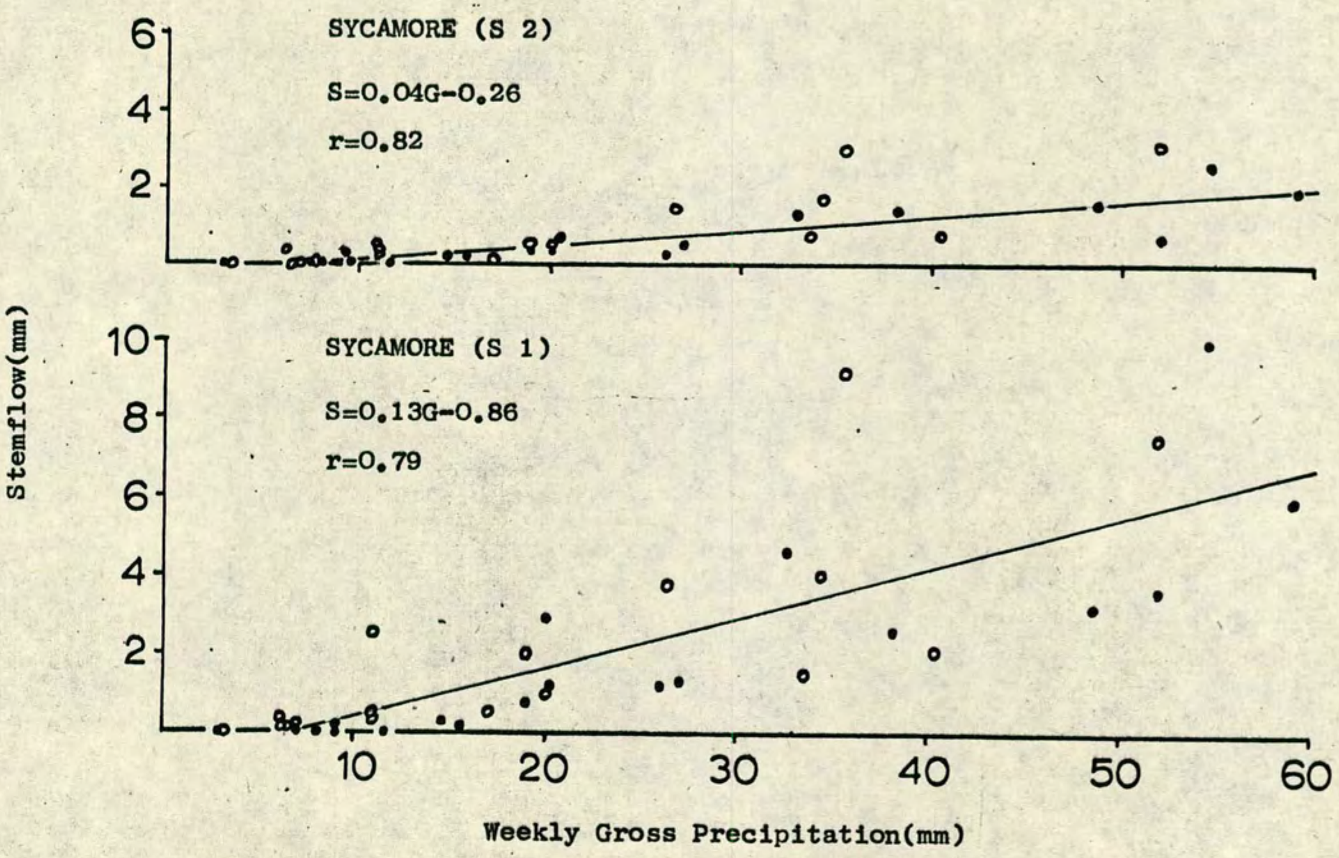
Regression analysis and analysis of covariance was also applied to the weekly stemflow data to test for species and seasonal variations. The stemflow values were plotted against gross precipitation as shown in Figure 28. It is clear from these scatter diagrams that no straightforward distinction can be made between winter and summer data points. For this reason, analysis of regression was applied to the pooled data regardless of the seasons and the regression equations shown also in Figure 28 were compared by means of the analysis of covariance. The results showed significant differences in terms of the slope of these equations between the Beech and Sycamore and between the two Sycamore sites. The regression slope for Beech (Be 2) is 0.21 against 0.13 and 0.04 for the Sycamore sites of S1 and S2 respectively. The difference between the two Sycamore sites may be attributed to the one in Compartment 13 (S2) being sheltered by large trees, whereas the marked difference between the Beech (Be 2) and Sycamore (S1) in Compartment 11 must be a real species variation. This is because the latter difference was detected from the two neighbouring sites where identical degrees of exposure occur.

IV.2.3 Interception by Deciduous Trees

Weekly interception values estimated by Formula 3 have already been given in Table 22. Because of the differences in throughfall

Figure 28 The Scatter Diagrams of Stemflow on Deciduous Species. Summer (•), Winter (∘).




SYCAMORE (S 2)
S=0.04G-0.26
r=0.82
SYCAMORE (S 1)
S=0.13G-0.86
r=0.79
Stemflow(mm)
Weekly Gross Precipitation(mm)
6
4
2
10
8
6
4
2
10
20
30
40
50
60

and stemflow between the sites, differences are also evident in terms of interception loss. They can be seen from Table 25 where total interception values for the leafy and leafless periods are given. It should be noted that in these estimates, the three negative interception values mentioned earlier were taken as zero. Figures in this table show clearly that 30% of the total precipitation of 487.7mm was caught by and evaporated from the Beech canopy. Although winter interception appears to be slightly greater in proportion (33%), it is believed that this is because of deficiencies in the data for the winter period. Certainly one would not expect higher interception during the period of the year in which the trees have no leaves. Table 25 also indicates that a considerably lower proportion of rainfall was intercepted by the Sycamore trees on two different sites. At site S1, interception accounted for 15% and 10% for the summer and winter periods respectively amounting to an average of 12% for the whole period. A decrease of 5% is evident as can be expected during the leafless period. Site S2, on the other hand, gave a higher interception loss than S1, amounting to 26% and 15% for the summer and winter periods respectively, with an average of 21%. The difference between S1 and S2 occurred despite great similarity of the tree crowns and canopy structure. Therefore, it appears that the difference can be considered to have originated from the different locations of the two sites in relation to exposure. It has already been pointed out that the trees at site S2 are surrounded by high mature deciduous trees with well developed crowns. It is likely that these intercept some of the precipitation that would otherwise fall on this site. This, in turn, could result in an overestimation of interception at site S2.

Table 25 Seasonal Interception Losses from the Deciduous Species.

	G(mm)	INTERCEPTION Be 2 mm	%
Summer	400.2	119.5	30
Winter	87.5	28.9	33
Total	487.7	148.4	30

		INTERCEPTION			
		S 1		S 2	
	G(mm)	mm	%	mm	%
Summer	475.0	68.8	15	122.5	26
Winter	339.9	34.5	10	51.2	15
Total	814.9	103.3	12	173.7	21

G = Gross Precipitation

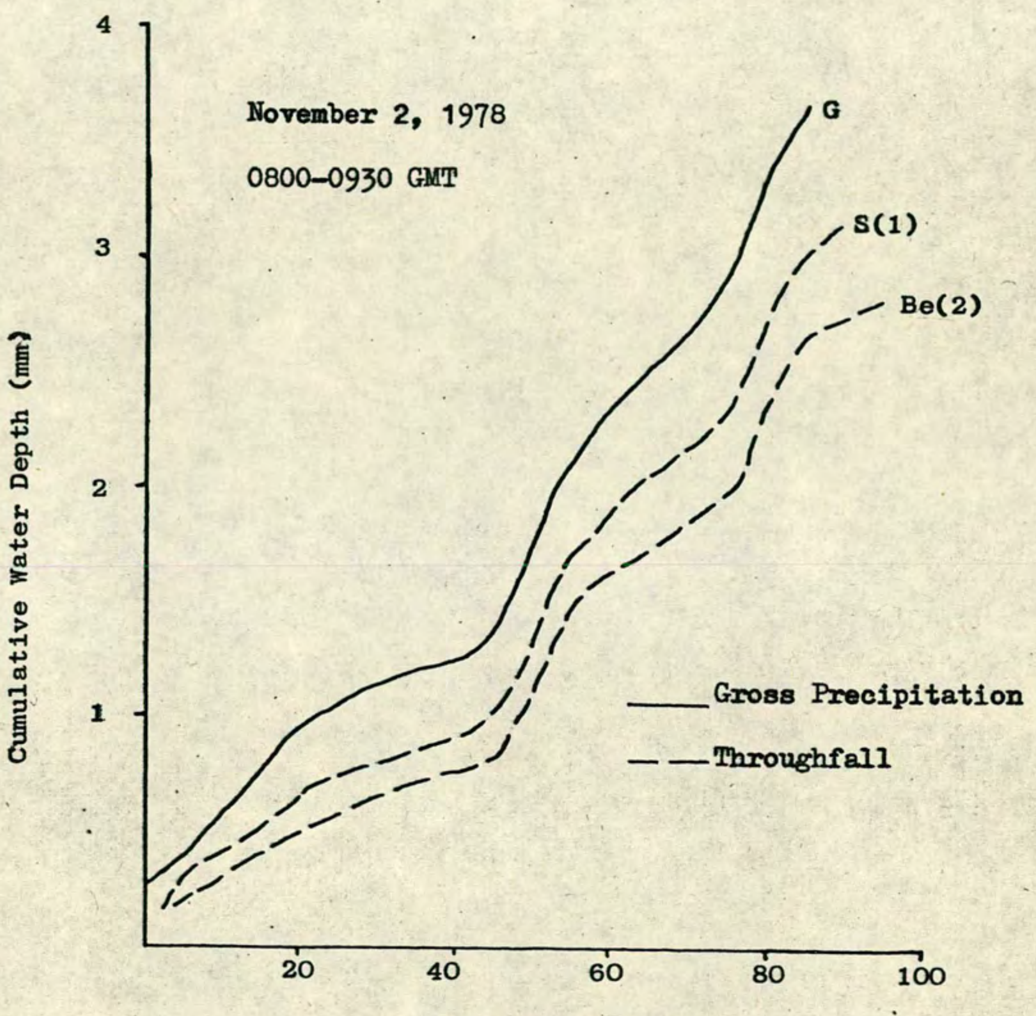
Whereas at site S1, the Sycamore trees were not sheltered in such a way and therefore the results for this site might be considered more reliable and better representative of the species. On these premises when the figures in Table 25 are compared against each other, it can safely be concluded that the Beech trees intercepted approximately twice as much precipitation as the Sycamore ones. This is attributable to the different canopy structure and density of the two species as described already in IV.2.1.

An attempt was made to determine the capacity of the deciduous canopies of holding water, i.e. canopy storage capacity, in order to provide a basis for an explanation of the differences already shown between the species. To achieve this, the same procedure was adopted as for the Pine stand. The interception values of 1.2mm, 0.6mm and 0.7mm shown in Table 22 for the period 30 June - 6 July 1977 for Beech (Be 2), Sycamore in Compartment 11 (S1) and Sycamore in Compartment 13 (S2) respectively were taken as the canopy storage capacity values. It is clear from these values that the Beech canopy is capable of retaining twice as much water at a time than the Sycamore. Since sites S1 and Be 2 are in neighbouring small plantations, it must be considered that the same evaporative conditions, such as wind speed and available solar energy, prevailed. It is, therefore, concluded that the difference in interception loss detected between the two species (12% and 30%) arose from the different canopy storage capacity given above. In other words, the Beech trees caught much more water during each rain shower than the Sycamore trees, resulting in a greater interception loss for the experimental period as a whole.

This is better illustrated in Figure 29 where the cumulative throughfall values during a small and short rain shower are plotted against the time. The necessary information was obtained from the experiment with tipping-bucket devices installed under the Beech and Sycamore trees in Compartment 11. Figure 29 clearly shows that throughfall started shortly after the rain had commenced, following a similar trend with gross precipitation. However, Figure 29 does not give information on stemflow for the same shower. Nevertheless, it has already been shown earlier in this section that, although stemflow was greater on Beech than Sycamore, net precipitation under the former still amounted to much lower values than the latter. It is, therefore, considered that the cumulative throughfall values shown in Figure 29 are informative at showing the different rainfall distributions under the two different species, resulting in different interception losses.

Data on separate rainfall showers obtained both at Dalmeny Estate and at Turnhouse Airport were studied in relation to the above canopy storage values in the same manner used earlier for Pine results. It was found that the interception losses from the deciduous trees were almost entirely due to the canopy storage rather than to the evaporation of the intercepted water. The average rate of evaporation from the wet canopy during precipitation was found to be very low (less than 0.05mm/hour), which is probably due to the small height of the Beech and Sycamore trees presenting an aerodynamically unfavourable condition for evaporation as opposed to the tall Pine trees in Compartment 12, where the evaporation rate amounted to 0.15-0.36 per hour.

Figure 29 Cumulative Gross Precipitation(G) and Throughfall in Sycamore(S1) and Beech(Be2) During a Storm on 2 November 1978. Data from Tipping-Bucket Raingauges.



IV.3 Discussion

The purpose of this section is, firstly, to compare the results obtained from Pine, Beech and Sycamore at Dalmeny Estate, secondly, to compare them with those reported in the literature by various investigators and, finally, to discuss the results in the context of the role of interception in the water balance of forests.

IV.3.1 Canopy Storage Capacity

It has already been mentioned that the storage capacity of the forest canopy is one of the most important factors controlling the amount of interception loss. It is useful, therefore, to compare and discuss the canopy storage capacity values found at Dalmeny Estate and in the literature.

The values obtained from the present and previous experiments are summarized in Table 26. Although many estimates have been reported in the literature, only those of the same tree species used in the present work are listed in this table, i.e. Pinus spp, Fagus spp. and Acer spp. This is to provide a basis for direct comparison. The figures in Table 26 clearly show that Pine at Dalmany has a storage capacity of 0.4-2.2mm against 1.2mm for Beech and 0.6-0.7mm for Sycamore. During winter, the Beech and Sycamore values might be even smaller. The results reported in the literature for Pine vary with a similar range of 0.3-3.0mm. It can be seen from Table 26 that Rutter's forest (Bramshill, Berkshire) has a canopy storage capacity

Table 26 The Canopy Storage Capacity Values Obtained from the Present Work and from the Literature.

			C.Storage Capacity (mm)
i) Pinus spp.			
Dalmeny	*Pinus sylvestris*	Plot 1	0.4
Dalmeny	" "	Plot 2	1.3
Dalmeny	" "	Plot 3	2.2
Rutter(1963)	" "		1.4- 1.8
Niederhof & Wilm(1943)	*Pinus contorta*		0.8
Kittredge(1953)*	*Pinus ponderosa*		0.3
Rowe & Hendrix(1951)	" "		3.0
Johnson(1942)*	" "		0.8 - 1.3
Grah & Wilson(1949)	*Pinus radiata*		0.3 - 1.0
Voigt & Zwolinski(1964)	*Pinus resinosa*		0.8
Voigt & Zwolinski(1964)*	*Pinus strobus*		0.5
Kittredge et al(1941)	*Pinus canariencis*		0.5 - 1.0
ii) Fagus spp. and Acer spp.			
Dalmeny	*Acer pseudoplatanus*	(S 1)	0.6
Dalmeny	" "	(S 2)	0.7
Dalmeny	*Fagus sylvatica*	(Be 2)	1.2
Delfs(1967)	" "		2.0
Horton(1919)*	Mixed(*Acer*, *Ulmus*, *Betula*, *Quercus*)		0.5-1.8
Singh & Szeicz(1979)	Mixed(*Fagus grandifolia* and *Acer saccharum*)		2.4

(*) Reported in Zinke(1967)

of 1.4-1.8mm which appears to be closest to the Dalmeny values. As to the deciduous species, very little data has been reported in the literature. The canopy storage capacity of 0.5-1.8mm reported for Horton's mixed forest is in close agreement with the present work. The results reported by Singh and Szeicz (1979) and by Delfs (1967), on the other hand, are extremely high which might be due to a much denser canopy density. These similarities and dissimilarities in the canopy storage capacities ought to be borne in mind when comparing the interception values obtained from various experiments.

IV.3.2 Stemflow

Stemflow has often been reported to be negligible in Pine whereas it is usually a considerable portion of the gross precipitation in Beech and Sycamore. This is shown in Table 27 where the results obtained from the experiments at Dalmeny and from the literature are summarized as percentages of the gross precipitation. This table clearly shows that stemflow accounts for 1-2% in Pine. Rutter (1963), on the other hand, reported 15% of stemflow. This is extremely high compared with the other work reviewed. Rutter (1963) attributes this to the funnelling effect of branches ascending at an acute angle from the trunk in his young trees. Similarly, Ford and Deans (1978) also reported a high proportion of stemflow (27%) in Sitka Spruce in Southern Scotland, where identical branching characteristics occur. However, such an effect is not exerted by mature trees which have different crown structure from the young tree. Moreover, in the case of Rutter's experiments, high

Table 27 Stemflow Values obtained from the present Work and from the Literature

i) Pinus spp.

			Stemflow (%)
Dalmeny	*Pinus sylvestris*	Plot 1	2
"	"	Plot 2	1
"	"	Plot 3	1
Rutter (1963)	"		15
Gash & Stewart (1977)	"		2
Ovington (1954)	*Pinus nigra*		< 1
Voigt (1960)	*Pinus resinosa*		1
Wilm (1943)	*Pinus contorta latifolia*		< 1
Rowe & Hendrix (1954)	*Pinus ponderosa*		4
Johnson (1942) *	"		0
Kittredge et al (1941)	*Pinus canariences*		1

ii) Fagus spp. and Acer spp.

Dalmeny	*Acer pseudoplatanus*	(S1)	9
"	"	(S2)	3
"	*Fagus sylvatica*	(Be2)	17
Delfs (1967)	"		16
Voigt (1960)	*Fagus grandifolia*		9
Moore et al (1924) cited by Kittredge (1948)	Maple and Beech		6
Riegler (1881) cited by Molchanov (1960)	Beech		13
"	Maple		6

* Reported in Zinke (1967)

stemflow was associated with low throughfall which resulted in interception estimates comparable to most of the other experiments conducted in Pine.

It is apparent from Table 27 that the deciduous species under study yield considerably more stemflow than Pine, amounting to as much as 17% of the gross precipitation. The results obtained from the present experiment are in broad agreement with those reported in the literature. It has often been stated that this difference is due to the fact that most deciduous species have smooth bark that can be wetted quickly and, therefore, more water usually runs down the trunk as stemflow. It has already been shown that stemflow on Sycamore was increased after leaf-fall during winter. However, these seasonal variations are not shown in Table 27, since other investigators reported only average stemflow values regardless of seasons. Apart from the very marked difference shown in Table 27 between Pine and the deciduous species, an important difference in stemflow is also evident between Fagus spp. and Acer spp. At Dalmeny, for example, stemflow amounted to 17% on Beech against 3-9% for Sycamore. Riegler's (1881) results appear to confirm this, i.e. 13% and 6% for Beech and Maple respectively.

IV.3.3 Throughfall

In an attempt to compare the results of the various experiments, a literature study has been carried out; a summary of which is given in Table 28. Throughfall results have been reported in the literature either as percentages of gross precipitation or regression equations. In Table 28, only percentages are given since they provide a means of direct comparison not affected by the amount of actual periodic or annual precipitation. Most regression equations reported in the literature are based on the volume of precipitation per shower and are, therefore, not comparable with the regression equations of throughfall presented in the present work, since they were calculated from weekly data.

Table 28 shows that 52-67% of the gross precipitation fell as throughfall under Pine stands at Dalmeny during the whole period of measurement. This result is in agreement with those reported by Rutter (1963), Gash and Stewart (1977), Ovington (1954) and Wilm (1943). The other experiments, all reported in the USA, yielded much higher throughfall portions, often exceeding 80%. It is, however, difficult to account for this difference. One reason might be the difference in canopy structure (i.e. less dense). For example, Voigt (1960) measured 80% throughfall in a thinned Red Pine forest with 500 trees per hectareand 85% canopy closure. Whereas over 1200 trees per hectar were counted at Dalmeny, the corresponding figures for Gash and Stewart (1977) and Rutter's (1967) sites are 800 and 4600 trees per hectare. It is clear that greater throughfall is associated with a lesser tree (or canopy) density. (See also Appendix 1).

In the case of the deciduous species studied 55% and 76-79% throughfall were measured under Beech and Sycamore at Dalmeny respectively. It has already been shown that seasonal variations were

Table 28 Summary of the Throughfall Results obtained from the present Work and from the Literature

i) Pinus spp.

		Throughfall (%)
Dalmeny	Pinus sylvestris Plot 1	64
"	" Plot 2	67
"	" Plot 3	52
Rutter (1963)	"	53
Gash & Stewart (1977)	"	62
Ovington (1954)	Pinus nigra	53
Voigt (1960)	Pinus resinosa	80
Wilm (1943)	Pinus contorta latifolia	68
Rogerson (1967)	Pinus taeda	86
Rowe & Hendrix (1954)	Pinus ponderosa	84
Johnson (1942) cited in Zinke (1967)	"	84
Kittredge et al (1941)	Pinus canariences	73-83

ii) Fagus spp. and Acer spp.

Dalmeny	Acer pseudoplatanus (S1)	79
"	" (S2)	76
"	Fagus sylvatica (Be2)	55
Delfs (1967)	"	76
Voigt (1960)	Fagus grandifolia	66
Moore et al (1924) cited in Kittredge (1948)	Maple and Beech	51
Ebermayer (1873) cited in Molchanov (1960)	Beech	83
Riegler (1881) cited in Molchanov (1960)	"	65
"	Maple	71

detected. However, they are not shown in Table 28 since most of the previous results are averages regardless of season. It is clear from this table that, although fluctuations occur, the results are in a similar range. In the present experiment, a marked difference between Beech and Sycamore is evident. No other experiment has been reported on both species in the same locality. However, Riegler's results for Beech and Maple (65% and 71% respectively) seem to confirm the results obtained from the present experiment at Dalmeny.

IV.3.4 Interception Loss

It has been shown that the Pine canopy at Dalmeny intercepted 34-47% of the gross precipitation recorded during a 13-month period. This result is compared in Table 29 with those reported in the literature for the same species. Interception values reported by investigators are listed in this table in the same way as for stemflow and throughfall in Table 27 and 28. Figures in Table 29 indicate that the proportion of interception to gross precipitation varies considerably from one experiment to another within the range of 12-46%. However, half of the results listed fall in the upper portion of this range with interception greater than 30%. One striking feature is the close agreement between the Dalmeny results and those reported elsewhere in Britain by Rutter (1963), Gash and Stewart (1977) and Ovington (1954) who measured interception loss to amount to 32%, 36% and 46% respectively. It has already been shown, for example, that Rutter's Pine forest has a canopy storage capacity similar to that for the Pine stands at Dalmeny.

Table 29 Summary of the Interception Results Obtained from the Present Work and from the Literature.

			Interception(%)
i) Pinus spp.			
Dalmeny	Pinus sylvestris	Plot 1	35
"	"	Plot 2	34
"	"	Plot 3	47
Rutter(1963)	"		32
Gash & Stewart(1977)	"		36
Ovington(1954)	Pinus nigra		46
Voigt(1960)	Pinus resinosa		19
Wilm(1943)	Pinus contorta latifolia		32
Mitchell(1930)	Jack pine		22
Rogerson(1967)	Pinus taeda		14
Rowe & Hendrix(1954)	Pinus ponderosa		12
Johnson(1942) cited in Zinke(1967)	"		16
Ebermayer(1873) cited in Molchanov(1960)	Pinus spp.		33
Morozov(1926) cited in Molchanov(1960)	"		23-32
Kittredge(1948)	"		16-40
Wood(1937)	Pinus rigida		15
Kittredge et al(1941)	Pinus canariences		17-28
ii) Fagus spp. and Acer spp.			
Dalmeny	Acer pseudoplatanus	(S 1)	13
"	"	(S 2)	21
"	Fagus sylvatica		30
Delfs(1967)	"		8

Continued/. . .

Table 29 (Cont'd)

		Interception(%)
Voigt(1960)	*Fagus grandifolia*	25
Singh & Szeicz(1979)	Mixed	30
Moore et al(1924)cited in Kittredge(1948)	Maple & Beech	43
Riegler(1881) cited in Molchanov(1960)	Beech	22
"	Maple	23
Beall(1934) cited in Zinke (1967)	Mixed	20
Ebermayer(1881) cited in Molchanon(1960)	Beech	17

Results for the deciduous species are also listed in Table 29. In the present discussion, seasonal variations that have already been shown are ignored as for the throughfall to provide direct comparison with the previous experiments. At Dalmeny, Beech intercepted on average 30% of the gross precipitation against 12% and 21% for the two Sycamore sites. Results reported in the literature for the same species vary widely from 8% (Delfs, 1967) to 43% (Moore et. al., 1881). However, apart from these extremes, a range of 15-30% is evident, which is consistent with the findings obtained from the present experiment.

It is evident from the preceding discussion that the findings at Dalmeny are in broad agreement with those obtained by other workers using comparable species. It is logical, therefore, to assume that the present results for different species at Dalmeny should be compared and discussed in more detail.

It has already been shown that Pine stands at Dalmeny intercepted on average 34-47% of the gross precipitation against 30%, 21% and 12% for Beech and the two Sycamore sites respectively. It is clear from these results that Pine intercepted much more precipitation than the deciduous species. It is also clear, however, that a large difference occurred between the two deciduous species than that between Pine and Beech. High interception loss from Pine may be accounted for by its greater canopy storage capacity (0.4-2.2mm) than Beech (1.2mm) and/or Sycamore (0.6-0.7mm). It has already been discussed that the water intercepted by the Pine canopy evaporated much faster than the Beech and Sycamore sites. This is, however, not surprising since the Pine site consisted of taller trees with a higher degree of exposure to wind effects than the short and young Beech and Sycamore. Here a question may arise as to whether the difference between Pine and the deciduous species is due rather to the difference in age and development stage than to a real difference between the two species. It may nevertheless be considered to be a real difference. We know from Delfs (1967), for example, that Spruce stands intercepted more than Beech at the same age (100 years) and in identical quality class. He reports that this is because Spruce had a dry weight foliage of 14,000 kg/ha against 2,650 kg/ha for Beech, resulting in considerable difference in interception storage capacity between the two species. It might, therefore, be considered that similar differences in interception would have likely been detected had the stands of Beech and Sycamore at Dalmeny been as old as the Pine stands.(See Appendix 1).

IV.3.5 A Discussion on the Role of Interception in the Water-Balance of Forests

It is relevant and of importance to discuss the role of interception in the water-balance equation for the forest types studied. In the present experiment, however, no determination of the necessary water-balance components, such as runoff, drainage, changes in soil moisture or transpiration by trees, was made. Therefore, the present discussion is bound to be tentative in character based on work reported elsewhere in Britain for the same forest and climate types. Some meteorological data collected by the Meteorological Office for the Edinburgh area, notably at Turnhouse Airport, can also be used to provide as much information as possible on the water-balance components of the site.

As far as the interception loss and its place in the water-balance are concerned, three important experiments have been reported in the literature. These are the experiments that have been undertaken in Thetford Forest, Hafren Forest and on the catchment of the Stocks Reservoir. Of these, Thetford Forest is the most similar site to Dalmeny, where the present experiment was conducted. First of all, Thetford Forest consists of Scots Pine, whereas in the Hafren and Stocks Reservoir experiments, the species studied were Norway Spruce and Sika Spruce respectively. Apart from the timber species point of view, Thetford Forest can also be considered to be similar to Dalmeny in terms of the rainfall regime. Both Dalmeny and Thetford are relatively dry sites with an average annual precipitation of 685mm and 583mm respectively, against the very wet Hafren and Stocks sites with annual precipitation of 1,350mm and about 2,700mm respectively.

The water-balance of Thetford Forest reported by Stewart (1977) and Gash and Stewart (1977) for the calendar year of 1975 is given in Table 30. Given in this table is also some information on some available water-balance terms for Pine stands at Dalmeny. Although the gross precipitation measurements in the present experiment spanned an 18-month period, it did not embrace a whole calendar year. For this reason, the annual precipitation (733mm) was obtained from the Turnhouse daily data sheets for 1977. Total potential evaporation estimated for short grass (albedo = 0.25) by Penman's formula was also obtained from the Meteorological Station at Turnhouse Airport. As has already been mentioned, terms such as actual evapotranspiration, transpiration and drainage (or runoff) are not known for the Pine stands at Dalmeny.

Table 30 Water Balance of Scots Pine at Thetford Forest for 1975, and at Dalmeny during 1977. (Partly After Gash & Stewart, 1977; Stewart, 1977)

		Dalmeny	
	Thetford	Plot 1	Plot 3
Annual Precipitation(mm)	595	733	733
Potential Evapotranspiration(mm)	643	668	668
Actual Evapotranspiration(mm)	567	-	-
Drainage and Runoff(mm)	28	-	-
Transpiration(mm)	353	-	-
Interception(mm)	214	257	345
Interception(%)	36	35	47
Saving in Transpiration(mm)	69	83	111
Net Interception Loss(mm)	145	174	234

However, these terms may be considered to be similar to those of Thetford Forest because of the considerable similarity between the two sites. Interception loss, on the otherhand, was estimated for two typical plots (Plots 1 and 3) as 35% and 47% of the 733mm annual precipitation, i.e. 257mm and 345mm respectively.

Table 30 shows that 595mm rainfall fell at Thetford Forest during 1975. Of this amount, 567mm was measured as total evaporation from Scots Pine which is 76mm short of the estimated potential evaporation (643mm). The total actual evaporation included 353mm transpiration by trees and 214mm interception loss which in turn included 27mm interception by a bracken undergrowth (not shown in Table 30). Stewart (1977) showed that on average the rate of evaporation of intercepted precipitation was 3.1 times the rate of transpiration under the same radiation conditions. It follows that the presence of intercepted precipitation on the canopy suppressed 69mm of transpiration, giving a net interception loss of 145mm for 1975. If the same ratio is applicable to the Dalmeny conditions, then the water saving in transpiration will amount to 83mm and 111mm at Plots 1 and 3 respectively, giving a net interception loss of 174mm and 234mm respectively. The reason for a greater interception loss at Dalmeny is of course because it receives a greater volume of annual precipitation than the Thetford site (Table 30). These estimated amounts of suppressed transpiration really mean that they should probably not be attributed to the interception process because such volumes of water would, in any case, be evaporating in the form of transpiration. It must be pointed out, however, that in the case of Thetford Forest transpiration during

1975 was determined only for the periods during which the canopy remained dry. For this reason, the estimated suppressed transpiration (69mm) is not a separate term in the water balance equation of that site.

It has already been shown that the total evaporation from Thetford Forest during 1975 did not exceed the estimated potential evaporation despite experimental results indicating that intercepted water evaporated about three times faster than transpiration under the same radiation conditions. In the first instance, this appears to be a discrepancy. It has already been mentioned, however, that tall crops, such as forest, exert considerable control on transpiration, so that the transpiration rate is substantially less than the Penman estimate for short grass. Total actual evaporation from any forest is, therefore, determined by the lengths of period during which the canopy remains wet or dry. In the case of Thetford Forest as a relatively dry site, the forest canopy is mostly dry transpiring. Whereas, we know from Calder's (1976) work that the total actual evaporation from forests located in a wet region exceeds the Penman estimate considerably. In the case of Hafren Forest, Calder (1976) reported 1,100mm of actual evaporation (790mm of which is interception) from Norway Spruce against the Penman estimate of 390mm for short grass. It may be considered that, in the case of Dalmeny, it is very likely that total actual evaporation is in the range of the Penman estimate, since the site is similar to Thetford Forest rather than to the Hafren Forest in terms of the wetness.

Although the total evaporation per annum from the Pine stands at Dalmeny may not be greater than the Penman estimate, it must be pointed out that this does not apply to the seasonal variations. It has already been shown that, although precipitation is fairly uniformly distributed throughout the year, water deficit in summers and surplus during winter occur due to considerable seasonal variations in the potential evaporation (See II.1.2.6). In Table 31, periodic interception loss in Pine and the Penman estimates of the potential evaporation at Turnhouse are given. The figures clearly indicate that interception loss alone can considerably exceed the Penman estimate during some winter periods. The periodic interception values shown in this table were estimated from the weekly values presented already in Table 15 (see IV.1). Since a continuous record is not available for the period of 31 December 1977 - 1 March 1978, rainfall of 115.8mm for this period was obtained from the Turnhouse daily data sheets and the corresponding interception of 40.5mm and 54.4mm for Plots 1 and 3 were estimated as 35% and 47% of rainfall respectively. The figures in Table 31 indicate that potential evaporation for the same period is only 12.5mm. For another two-monthly period of 2 November to 30 December 1977, interception amounted to 50.4 to 68.5mm against the Penman estimate of 64.7mm. When evaporation other than interception is takeninto account, it is likely that the total evaporation occurred during this period was also in excess of the Penman estimate. These findings are consistent with the results reported by Law (1957) who measured 108mm interception in Sitka Spruce while the Penman estimate of open water evaporation was only 7.4mm between 19 December 1955 to 11 March 1956. It can, therefore, be concluded from the discussion

Table 31 Comparison of Interception by Pine at Dalmeny with Potential Evapotranspiration Calculated at Turnhouse Airport by the Penman Formula.

Period	Rainfall at Dalmeny (mm)	Potential Evapotranspiration (mm)	Interception by Pine (mm)	
			Plot 1	Plot 3
1977				
June 24 - August 23	61.7	182.2	30.5	38.6
August 24 - Nov. 1	244.8	132.1	57.5	86.4
Nov. 2 - Dec. 30	130.4	64.7	50.4	68.5
1978				
Dec. 31 - March 1	115.8	12.5	40.5	54.4
March 2 - April 25	68.5	74.4	31.2	43.2
April 26 - July 28	173.2	263.2	66.2	82.0

so far that interception of precipitation represent an extra water loss and, therefore, should be determined and placed in the water-balance equation separately.

Having discussed the role of interception in the water-balance of Pine forest, a similar discussion is also needed for the species of Beech and Sycamore. Singh and Szeicz (1979), for example, reported in their recent paper on the water-balance of an undisturbed mixed hardwood forest in Quebec (Canada), the dominant species being American Beech (Fagus grandifolia Ehrh.) and Sugar Maple (Acer saccharum Marsh). During the summer of 1975 (29 May - 7 October), they recorded 442mm of precipitation while the forest transpired 261mm and intercepted 111mm. The runoff amounted to 131mm during the same period in which the change in soil moisture storage was determined to be -52mm. Singh and Szeicz (1979) showed from these measurements that the closure of the balance was very good (+9mm), but it would amount to as much as -102mm if the interception was not taken into account, indicating the important place of interception in the water-balance equation. It must be said that these results cannot really be extrapolated to Dalmeny where different forest parameters and climatological conditions occur. No investigation has been reported, however, into the water-balance of the same species under similar conditions elsewhere in Britain. For this reason, no use can be made of data from the literature, although it would have been useful to have been able to discuss the role of interception in these timber species. However, the evidence obtained from the present experiment at Dalmeny appears to suggest that Sycamore intercepts considerably less precipitation than Beech and

Pine, and therefore from a hydrological point of view, Sycamore ought to be considered a better choice than Pine or Beech in catchment areas where there is a great demand for water. However, it is recognized that a firm conclusion on this matter cannot be made until detailed information is available concerning the relative roles of evaporation and transpiration in Sycamore stands in this area.

PART V

CONCLUSIONS

Interception of precipitation by forests has long been under study in various parts of the world. Investigators in different fields, such as forestry, agriculture, meteorology and hydrology, have shown increasing interest in the subject for various purposes from various points of view. The results that have been compiled so far have highlighted problems of accurate determination of interception loss, its role in the water-balance of catchments and the difficulty of extrapolating results obtained in one locality to other regions and forest types. Recent work in Britain has indicated, for example, that interception of rainfall is of far more hydrological importance than appreciated hitherto (Rutter 1963 and 1967, Stewart and Thom 1973, Gash and Stewart 1977, and Calder 1976). The present work was carried out to report on various aspects of interception as a contribution to the increasingly interesting current discussion. The conclusions that can be drawn from this work fall into two parts. The first part is concerned with matters relating to the instrumentation and measurement problems involved in determining gross precipitation, throughfall and stemflow. The second part consists of conclusions that can be drawn from the estimates of interception loss obtained from the present experiment.

V.1 Conclusions on the Instrumentation and Measurements Problems

It has long been appreciated that accurate measurement of precipitation at any location presents one of the most difficult tasks in hydrological experiments. This is due to the disturbing effect of wind on raingauge catch which usually results in underestimation of this quantity (Rodda 1967, Green 1970 and Ward 1975). In any interception experiment, it is desirable to measure as accurately as possible the amount of precipitation landing on the forest canopy. Experiments conducted by Law (1957) and Reynolds and Leyton (1965) showed that rainfall measurements just above the forest canopy are subject to large errors from the above-mentioned wind effect. For this reason, in many interception experiments, gross precipitation has been measured in forest openings rather than at canopy level. In the present experiment, this approach was adopted and it was assumed that gross precipitation measurements made outside the forest and in forest openings at Dalmeny would give accurate estimates of the rainfall landing on the forest canopy. It must be recognized, however, that this assumption could be in error. A weakness of the present experiment is that it was not possible to undertake the work needed to resolve this issue.

The present experiment was conducted in a small area where the tree stands are subject to exposure to wind. It must, therefore, be recognized that precipitation over the forest canopy may not be evenly distributed. It is generally accepted that the presence of an edge may cause extra turbulence which may in turn increase the rainfall landing on the forest edge. However, it is difficult to assess this effect quantitatively.

Apart from the above-mentioned uncertainties that might be considered to be inherent in any measurement of gross precipitation, another source of error can arise from variation in precipitation which can result in different amounts being recorded at different locations. It is sometimes difficult to know whether recorded differences are due to spatial differences in rainfall amount or to observational errors. In the present experiment spatial variation was sampled by means of four to six gauges and only small differences were detected. Interception workers have usually decided on the number of gross precipitation gauges arbitrarily. Helvey and Patric (1965 a and b), on the other hand, have suggested that a proper number can be determined statistically based on the amount of spatial variation, tolerable error and the desired probability level. Their formula has been used and the results showed that the above number of gauges used in the present experiment was sufficient to achieve an average weekly gross precipitation with $\pm 5\%$ error at the 99% probability level.

It is clear from the above discussion that precise determination of gross precipitation presents a difficult task because of instrumental error and the effect of wind. However, the interception student is often not faced with any problem in dealing with spatial variation which dictates the number of gauges to be used. In the case of throughfall, on the other hand, the wind effect is usually unimportant because of the sheltering effect of the forest trees. The main consideration becomes instead the number of gauges to be employed because throughfall is usually distributed unevenly under forest canopies. In order to achieve accurate measurement of this variable, investigators have followed two different approaches:

i) By employing many gauges.

ii) By using large troughs so that variation in throughfall can be integrated.

It is not clear from the literature whether the use of troughs is superior to ordinary gauges. Helvey and Patric (1965 a) reported that only 20% fewer troughs were needed to achieve the same accuracy than the standard gauges with a diameter of 203mm. They, therefore, concluded that the number of gauges is more important than their size or type.

In the present experiment, throughfall was measured in Sycamore by means of both home-made plastic funnel gauges (152mm diameter) and a large 60° triangle perspex trough (104cm each side). The results obtained were compared and it has been shown that the trough gave only fractionally smaller throughfall readings than those obtained from ordinary gauges. The difference was found to be attributable to evaporation from the trough and to water retained on its large surface. It is, therefore, concluded that ordinary gauges are probably more suitable for measuring throughfall. Another advantage of ordinary raingauges of course is that they reveal how the throughfall varies from one location to another under the same forest canopy.

A literature survey was carried out and it was shown that investigators had used widely varying numbers of throughfall gauges in their experiments. These numbers had generally been chosen arbitrarily. Helvey and Patric (1965 a and b) suggested a formula that could be used to determine the number of throughfall gauges (neither too small nor too large) to achieve predetermined accuracy levels. In the present experiment throughfall was measured by means of 21 gauges in Pine, 8 to 11 guages in old Beech (Be 2), 7 to 21 gauges in young Beech (Be 2), 6 to 44 gauges in Sycamore (S1) and by means of 11 gauges in Sycamore (S2). (See Part III). Since the method suggested by Helvey and Patric requires information about the amount of variation in throughfall, the above numbers had to be decided on by considering, firstly, the results of the above-mentioned literature survey and, secondly, the practical factors limiting the maximum number of gauges that could be maintained by a single research worker. Estimates of numbers of gauges according to Helvey and Patric's approach were made in retrospect using information gathered on standard deviation of mean throughfall for each timber species. Although the estimated numbers of gauges required varied from one species to another, it has been shown that the present gauging was satisfactory for measuring average throughfall to within ±10% error at 95% probability, provided that the amounts exceeded 20mm per week. Accurate measurement of throughfall volumes lower than 20mm per week would have required considerably more gauges. However, since weekly values lower than 20mm account for only a small portion of seasonal or annual throughfall at Dalmeny, it is considered that a greater error can be tolerated for them. It is concluded that the present throughfall sampling was satisfactory at all sites except that which involved old Beech (Be 1), where high variations occurred between the point throughfall measurements. For this reason, the results obtained from old Beech were in great error and they have not been presented in this thesis.

Another important feature of throughfall measurement is how and where to install the gauges. Most investigators have measured throughfall in randomly selected locations (Wilm 1943, Ovington 1954, Law 1957, Rutter 1963 and Carlisle et al 1965). Some, however, have installed their gauges systematically and have reported the occurrence of patterns with throughfall generally increasing with distance away from the tree trunk (Voigt 1960, Ford and Deans 1978). Attempts were made in the present experiment to detect such relationships between throughfall catch and the distance of the gauge from the tree bases. None could be found. Instead, it has been shown clearly that throughfall is distributed in a random manner in all the stands under study. It has also been shown that in deciduous stands, notably mature Beech, so called "dripping points" occurred where extremely high volumes of throughfall were measured. It is, therefore, desirable to determine how many such locations exist in a given area and how much water reaches the soil surface. This subject appears to require special attention in future interception experiments.

It is desirable to know what portion of precipitation is retained by trees as canopy storage, and how much water evaporates from the wet canopy during precipitation. This usually involves recording what can be called individual rainfall events, because measurements carried out on a weekly basis cannot provide detailed information as usually more than one shower falls during a week as was the case of Dalmeny. To collect such detailed information, tipping-bucket devices were employed, and gross precipitation and throughfall were measured and recorded automatically by an event recorder. The design and construction of this equipment have been described. It has been shown that the employment of such instrumentation is of a special value although some difficulties were faced in construction and maintenance in the field conditions. Unfortunately, data obtained by this technique did not span a long period due to the time factor, and the results were not as useful as they might have been.

In any interception study, water that runs down tree trunks (stemflow) has to be taken into account. In the present experiment, stemflow was measured on small sample plots in each stand type, each consisting of five neighbouring trees. The volumes measured were converted into milimetres of water depth over the plot area. By following this plot approach, it is recognized that some error was avoided which could have occurred otherwise had stemflow been measured on randomly selected individual trees, the projection areas of which are more difficult to determine accurately. Although high variations were detected between the sample trees in a single plot, no significant difference was detected between any pairs of sample plots in the same forest type. It is, therefore, considered that the approach used was satisfactory and gave accurate results. It is natural of course that more accurate results would be obtained if stemflow had been measured on larger plots. This could not be achieved in the present work because it involves a great amount of work that is usually beyond the scope of a single research worker. This problem could be overcome by automatic data acquisition using sophisticated and costly gauges and data logging devices. Nevertheless, this may not be vital as stemflow often accounts for a small portion of the gross precipitation. It is, for example, negligible on Pine. Thus greater errors may be tolerated for stemflow measurements than those of throughfall.

It is recognized that the problem of obtaining accurate data on gross precipitation, throughfall and stemflow is linked very closely with automation of data collection and recording. This is so because, as has already been discussed, accuracy often means employing many gauges which, in turn, involves a great deal of work. Automation also improves the nature of the data as it enables observations to be made and recorded at very short time intervals which cannot be achieved by manual techniques. However, such effective methods of data acquisition are expensive and can only be fully employed by large research establishments, such as the Institute of Hydrology at Thetford Forest.

V.2 Conclusions drawn from the Experimental Results obtained

In the Pine stands at Dalmeny, measurements of throughfall and stemflow were undertaken on three small plots, one of which was situated on the forest edge (Plot 1) and the others in the interior of the forest at 50m of spacing (Plots 2 and 3). It has been shown that stemflow on Pine is negligible, amounting to 1-2% of the periodical gross precipitation. Thus, the net precipitation consisted almost entirely of throughfall. This is in agreement with the previous results reported in the literature and is generally attributed to the rough bark of Pine stands.

It has been determined that interception loss amounted to 35%, 34% and 47% of the gross precipitation on Plots 1, 2 and 3 respectively over a 13-month period from June 1977 to July 1978. These estimates were compared with experiments reported in the literature on Pine and it has been shown that the present results are consistent with those from previous experiments, in particular with those reported elsewhere in Britain by Ovington (1954), Rutter (1963) and Gash and Stewart (1977).

It is clear that a considerable difference in interception occurred between Plot 3 and both Plots 1 and 2. In absolute values, it corresponded to over 90mm of water during the whole experimental period. Data has been analysed by means of various statistical tests and the results showed clearly that this difference is not due to errors involved in measurements, but is real and significant. However, it has been found difficult to account for it. It is recognized that some of the difference may be due to an edge effect increasing precipitation landing on the forest margin (Plots 1 and 2). No quantitative estimate of such an effect was possible in the present work. It has been shown, tentatively, that most of the difference can really be explained by canopy storage capacity which was shown to amount to considerably more at Plot 3 than those for the other plots. However, the estimates of canopy storage capacity are probably not very reliable as they were based on interception data for a single week during which only one shower was recorded. Unfortunately, these estimates could not be repeated for another set of weekly data since,during all other weekly periods, more than one shower was recorded. Nevertheless, a study of the hemispherical canopy photographs taken vertically on the forest floor by means of a Nikkon camera with a fish-eye lense showed that the canopy at Plot 3 has a greater degree of density than the other plots. An implication of this is that variation in the canopy structure and density could result in a greater interception loss in association with a greater canopy storage capacity. This appears to imply that determination of interception is really a difficult task if representative results are to be obtained for a given forest type.

The experiment undertaken in the deciduous species at Dalmeny showed that the distribution of precipitation by the canopies of Beech and Sycamore does not follow the same pattern as for Pine stands. Stemflow, for example, accounts for a considerable portion of the gross precipitation, amounting on average to 17% on Beech and as much as 9% on Sycamore against only 1-2% for Pine. It has been shown that Sycamore and Beech are more suitable with their smooth bark and branching features for channelling more water down the tree trunk. An increase in stemflow was detected during winter which has been found to be attributable to a greater degree of exposure of branches to precipitation during the leafless period. These results were similar to those reported in the literature for the same species by Delfs (1967), Voigt (1960) and Molchanov (1960).

It has been shown that the greater proportion of stemflow on Beech and Sycamore was associated with throughfall values as much as throughfall under Pine or more. Thus the total amount of water reaching the forest floor in Beech and Sycamore was greater than Pine, resulting in smaller interception losses from Beech and Sycamore stands. On average, Beech intercepted 30% of the gross precipitation over the experimental period against 12% and 21% for the two Sycamore sites. Although a smaller portion of gross precipitation was intercepted during winter, it has been shown that the Beech and Sycamore stands still intercept a considerable amount of precipitation, probably more than expected. This indicates that branches are probably as effective as leaves in retaining precipitation on their surface. It is apparent that Sycamore intercepts considerably less than Beech and Pine.

It is concluded that differences in interception between these species must be due to differences in the canopy structure which can probably be best characterized by the canopy storage value. It has been shown that this is so as a smaller storage capacity of Sycamore is associated with lower interception loss. However, it must be noted that there is a real need for accurate determinations of the canopy storage values for the species under study.

In the present work, young Beech and Sycamore stands were compared with older Pine stands, and therefore the question arises as to whether, for example, Sycamore and Beech would intercept less than Pine if they were both of the same age. In the light of the information found in the literature, it is recognized that Beech and Sycamore would very likely intercept less precipitation if they were of the same age as for Pine stands (Delfs 1967 and Zinke 1967).

An attempt has been made to discuss and reveal the relative role of the interception loss in forests versus grass. It has been found that interception by Pine alone exceeded the potential evapotranspiration estimated during winter by the Penman Formula for short grass. We also know from Calder's (1976) work that total evaporation from forests can be several times greater than the estimated potential evaporation in a very wet area. Evidence in the literature indicates that the difference in the water consumption between forest and grass is attributed to fast evaporation from wet forest canopy during precipitation. In a relatively dry area, such as Thetford Forest and Dalmeny, actual total evaporation from forest can be considered not to exceed the potential evapotranspiration. This is because the forest canopy remains mostly dry transpiring. The results from Dalmeny provide further confirmation, therefore, that the very high interception losses reported in Central Wales are unlikely to be repeated in the drier parts of Eastern Britain.

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SCOTS PINE

PLOT 1

SCOTS PINE

PLOT 2

SCOTS PINE

PLOT 3

YOUNG BEECH (BE 2)

SYCAMORE IN COMPARTMENT 11 (S 1)

SYCAMORE IN COMPARTMENT 13 (S 2)